FLOW ABOUT AN OSCILLATING CYLINDER AND FREQUENCY SYNCHRONIZATION

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THESIS

Flow About An Oscillating Cylinder
And Frequency Synchronization

by

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ABSTRACT

The interaction between the forced oscillations of a cylinder in flowing water and its vortex wake as well as the flow-induced oscillations of a string-suspended cylinder are examined. In the former case, the frequency of the vortex shedding and the range of frequency synchronization are determined for each cylinder, flow velocity, and the amplitude and frequency of the forced oscillations. In the latter case, the amplitude and frequency of the oscillation of the suspended cylinder as well as the frequency of the vortex shedding are determined. Finally, the results are reported in terms of appropriate normalized parameters and interpreted in the light of existing information.

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NOMENCLATURE

A	Peak-to-peak amplitude of transverse cylinder displacement
D	Cylinder diameter
V	Mean free-stream velocity
f_c	Cylinder transverse-oscillation frequency
f_n	Cylinder transverse natural frequency
f_v	Vortex shedding frequency for the oscillating cylinder
f_s	Vortex shedding frequency for the stationary cylinder (Strouhal frequency)
V_R	Reduced velocity (V/f_vD)
ν	Kinematic viscosity of fluid
ρ	Fluid density
μ	Dynamic viscosity of fluid
f_{bsr}	The lowest value of f_c where $f_c=f_v$, i.e., the frequency f_c at which the synchronization commences
f_{esr}	The highest value of f_c where $f_c=f_v$, i.e., the frequency f_c beyond which the synchronization ceases.
A/D	Relative amplitude
Re	Reynolds number (VD/ν)
S	Strouhal number of f_sD/V

ACKNOWLEDGEMENT

The author is grateful to Professor T. Sarpkaya for his guidance and encouragement from the conception through the completion of this investigation.

I. INTRODUCTION

The objective of this study was to gain further insight into the complex interaction between a circular cylinder and its vortex wake when the cylinder is oscillating normal to the flow field. The various investigations have thus far fallen into two groups: (a) Mechanically forcing a cylinder to vibrate in a stream of water or air while measuring the vortex-induced forces acting on the cylinder along with their phase relationship to the imposed motion (1-5); (b) Elastically mounting a cylinder in an air or water stream and allowing it to vibrate under the influence of the alternating vortex while measuring the amplitudes of oscillation and in some cases the phase relation between the periodic wake and cylinder motion (2 4).

The presentation of these results has added considerable insight into the phenomenon and pointed out the extremely complicated nature of the problem and the need for further work.

The principal mechanisms exciting flow-induced vibrations of a single cylinder appear to be turbulence and vortex shedding. Turbulence may be considered to be comprised of localized velocity and pressure fluctuations occurring over a wide range of frequencies. When the resulting random excitation is imposed on an elastically mounted, lowly damped cylinder, it responds by extracting vibration energy only

within a narrow frequency band enclosing a natural frequency. The most significant is the fundamental natural frequency f_n of the cylinder.

The shedding of the Karman type vortices imposes alternating lift forces on a single cylinder as well as on many other types of bodies of practical importance and may give rise to hydroelastic oscillations (e.g. vanes and struts singing in water, singing ship propellers, strumming of hydrophone cables, vibration of submarine periscopes, vibration of mooring cables of naval mines, rudder-hull vibration, control surfaces on ships, heat-exchanger tubes, tall structures, etc.). The vortices are shed at a frequency determined by:

$$f_s = \frac{SV}{D}$$

where S is the Strouhal number, V is the flow velocity, and D is the cylinder diameter. As it is well known, the Strouhal number is the dimensionless parameter which characterizes the vortex shedding frequency in steady flow about a body at rest.

For the range of Reynolds numbers between 300 and 200,000 (including many practical applications cited above) S is approximately equal to 0.2. During each cycle two vortices are shed alternately from each side of the cylinder. The resulting alternating forces render the cylinder susceptible to lift-direction vibration at the vortex-shedding frequency, and to drag-direction vibration at twice the vortex shedding frequency.

When the flow conditions are such that the vortices are shed at or near either the forced frequency of an oscillating cylinder or the fundamental natural frequency of an elastically mounted cylinder, then the vortex shedding "locks in" with the cylinder oscillation. In other words, with the reduced velocity, $V_R = V/f_nD$ ranging in the vicinity of 5, the resulting "resonance" effects can cause large vibration amplitudes for an elastically-mounted cylinder and can synchronize the vortex shedding and cylinder-vibration frequencies.

The drag-direction excitation exists already at $V_R = 2.5$, at only one-half the velocity discussed above. While excitation at $V_R = 2.5$ has generally not been observed in air flow, water experiments (6) have shown that significant vibration amplitudes can be excited in the drag direction.

It is apparent from the foregoing that the occurrence of large vibration amplitudes may change the effective diameter of the cylinder and thus change the vortex shedding frequency and that the data obtained in air and water should be compared only with extreme care and due consideration of the governing parameters. In particular, it should be noted that (a) within a wide range of Reynolds numbers, the flow velocity determining the vortex shedding frequency is practically independent of the physical characteristics of the flow medium; (b) the density of water is about 800 times greater than that of air; (c) the magnitude of the excitation forces generated from turbulence and from vortex shedding are generally considered

to contain a factor that is proportional to the dynamic head ($\rho V^2/2$) of the flow. Since under about the same conditions of flow and thus frequency-dependent-vibration susceptibility, exposure to water exerts such tremendously large time-dependent drag and inertial forces than air that not only the absolute but also the relative influence of the excitation mechanisms can be expected to differ; and finally, (d) the damping effects of water immersion constitute an additional factor influencing the structural response.

The present investigation dealt primarily with the forced oscillation of a cylinder in water and to a limited extent with the free-oscillations of a string-suspended cylinder. In the former case, the frequency of the vortex shedding was determined for each cylinder, flow velocity, and the amplitude and frequency of the oscillation of the suspended cylinder as well as the frequency of the vortex shedding were determined. The results are reported in terms of appropriate normalized parameters and interpreted in the light of the existing information.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

The experiments described in this study were conducted in a low speed, free surface flow channel. This channel (Fig. 1) was of the recirculation type and has a test section 21 inches wide and 35 inches long. Uniform flow was maintained by installing a one inch thick honeycomb fifteen inches upstream and an adjustable weir ten inches downstream from the test section. Velocity was varied from 0.5 to 4.0 inches per second by changing the position of the weir and/or the speed of the recirculation pump. During all tests the depth of the water was maintained at four inches. Before any experiments were made, the velocity profile was determined by a hot-film anemometer. A profile, taken at the lower and upper ends of the velocity range, showed a flat center portion with a boundary layer thickness of approximately one inch on the sides and bottom. Obtaining a velocity profile for each experiment was very time consuming and did not lend itself to a direct setting of a desired mean free-stream velocity. Therefore, the float assembly shown in Fig. 2 was constructed. The time required for this float to travel thirty inches in the test section yielded the mean velocity, V. This value was in good agreement with velocity derived from the shedding frequency for a stationary cylinder. The float assembly was used as the primary measuring device and the shedding frequency as a check for all velocity determinations made during the first phase of this study.

Before any flow studies could be made, a means had to be devised by which the vortex street could be made visible. This was accomplished by spreading a small amount of aluminum powder on the surface of the water. A powder dispenser (Fig. 3) was suspended 0.50 inches above the water at the beginning of the test section, directly in line with the cylinder. The powder was dispensed from a container with a fine mesh-wire bottom by shaking it with an "L" shaped arm driven by a variable speed motor. The aluminum remained on the surface of the water provided the flow was such as to preclude the accumulation of large amounts of powder.

Vortex shedding frequencies were determined by timing the passage of ten vortices, generated from the same side of the cylinder, past a point five to ten diameters downstream from the cylinder, see Fig. 4.

The first phase of the investigation dealt with the forced transverse oscillations of a cylinder. A solid aluminum cylinder was held vertically in the flow with a 1/64 inch clearance from the channel bottom. The cylinder was supported by an aluminum block which rode on two rods positioned across the top of the channel (Fig. 5). A small variable-speed D.C motor drove a fly wheel with an adjustable stub-shaft which was in turn connected to the aluminum block and imparted a harmonic motion to the cylinder. The cylinder frequency was determined by timing ten complete cycles.

Each experiment was run to compare the cylinder frequency f_c, to the vortex shedding frequency f_v, with the amplitude, cylinder diameter, and the free-stream velocity held constant. The procedure for each run was to start with f_c well below the anticipated synchronization range, and increase f_c in small increments until well past the synchronization range (i.e., $f_c \neq f_v$). At each incremental increase of f_c the system was allowed to settle before determining a new f_v. The next run was then made with different combinations of the amplitude A, diameter D, and the mean velocity V. The values of A, D, and V used in each run are shown in Table I.

The second phase of the investigation dealt with the free oscillations of a cylinder and the measurement of A, D, V, f_c, and f_v. The cylinder assembly (Fig. 6) consisted of a 0.75 inch diameter, plexiglass cylinder attached to a small aluminum rod. The rod was fastened at the opposite end from the cylinder to a crossbar upstream from the test section. The cylinder end of the rod was suspended vertically by a 6 ounce fishing cord. This gave the cylinder a transverse pendulum type of motion while the rod maintained the cylinder in a vertical position. The natural frequency of the cylinder was determined by displacing the cylinder from its rest position and by timing the cycles of the free swing in four inches of still water.

The procedure for this type of a run was to pick a cylinder of desired diameter and natural frequency and vary the free-stream velocity. Each run was started at a low

TABLE I

RUN NUMBER	AMPLITUDE (inches)	CYLINDER DIAMETER (inches)	VELOCITY (in./sec)
1	1.000	1.00	1.28
2	0.500	1.00	1.16
3	0.250	1.00	1.16
4	0.750	0.75	1.66
5	0.375	0.75	1.67
6	0.187	0.75	1.665
7	0.562	0.75	1.52
8	0.250	0.75	1.68
9	0.187	0.75	1.62
10	0.125	0.75	1.62
11	0.500	0.75	1.66
12	0.312	0.75	1.66
13	0.625	1.25	0.98
14	1.000	1.25	0.971
15	0.500	1.25	0.971
16	0.250	1.25	0.975
17	0.187	0.75	0.809
18	0.187	0.75	2.06
19	0.250	1.00	1.97
20	0.562	0.75	1.44
21	0.937	1.25	1.30
22	0.937	1.25	1.24

velocity and then increased in small increments. Ateach increment the system was allowed to steady and the amplitude, cylinder-frequency, vortex-shedding frequency, and the Strouhal frequency were recorded. The velocities were calculated from the measured Strouhal frequency, i.e., $V = f_s D/S$. This procedure was continued until the vortex shedding frequency was once again approximately equal to f_s, after having passed through the synchronization range.

III. DISCUSSION OF RESULTS

The results of this experimental investigation will be discussed in three parts: (a) the exploration of the effects of forced oscillations on the vortex-shedding frequency; (b) exploration of the most suitable dimensionless parameters and the delineation of the synchronization range; and finally, (c) the observations of a freely-oscillating cylinder and the comparison of the results for the forced-and freely-oscillating cylinders.

The data obtained from the forced-oscillation tests are shown in Figs. 7 through 26. Evidently, the curves generated by plotting f_c versus f_v, regardless of the combination of cylinder diameter, peak-to-peak amplitude, and free-stream velocity, have the same general characteristics. In the range where $f_c < f_v$, the frequency of vortex shedding is approximately equal to the Strouhal frequency. The rate at which the vortices were generated was not constant but exhibited small variations. Such an observation was also described by Bishop and Hassan (1) and Toebes (17). They were able to isolate a beat frequency from the vortex shedding frequency. As the cylinder frequency was increased, the mixing of the various frequencies became more pronounced until the vortex frequency suddenly jumped to that of the cylinder frequency. This frequency, denoted by f_{bsr}, marked the beginning of the so-called "synchronization range" as

shown in Fig. 27. Within this range a vortex was shed each time the cylinder changed its direction and the center line of the vortex street oscillated from side to side, in a direction opposite to that of the cylinder. In the range of synchronization, the vortices were well defined and showed no consistent variations from the cylinder frequency. With further increases in the cylinder frequency, a particular state was reached where the vortex frequency suddenly jumped back to the Strouhal frequency. This particular frequency of the cylinder is denoted by f_{esr}. In the range where $f_c > f_{esr}$, the vortices again showed signs of multiple frequencies. This mixing of the frequencies increased with increasing relative amplitude.

Following a preliminary analysis of the data, in the manner discussed above, it was necessary to devise suitable normalized parameters which would, hopefully, yield meaningful relationships between the various dependent and independent variables.

For the case of the forced oscillations, the vortex-shedding frequency is dependent upon amplitude A, diameter D, free-stream velocity V, cylinder frequency f_c, fluid density ρ, and dynamic viscosity μ.

$$f_v = F\,(A,\ D,\ V,\ f_c,\ \rho,\ \mu) \qquad \text{(a)}$$

A simple dimensionless analysis yields the following one of the many possible sets of normalized parameters,

$$\frac{f_c}{f_v} = F\left(\frac{A}{D},\ \frac{\rho V D}{\mu},\ \frac{f_c D}{V}\right) \qquad \text{(b)}$$

which may be written, with the help of $S = f_s D/V$, as

$$\frac{f_c}{f_v} = F\left(\frac{A}{D}, \text{Re}, S\frac{f_c}{f_s}\right) \qquad (c)$$

At the two ends of the synchronization range, $f_c \cong f_v$ and thus

$$\frac{A}{D} = f\left(\text{Re}, S\frac{f_c}{f_s}\right) \qquad (d)$$

Since $S = f(\text{Re})$, one has

$$\frac{A}{D} = f\left(\text{Re}, \frac{f_c}{f_s}\right) \qquad (e)$$

Figure 28 is a plot of A/D versus f_c/f_s for a constant Reynolds number where $f_c = f_v = f_{bsr}$ and $f_c = f_v = f_{esr}$, i.e., for the frequencies at which the synchronization begins and ends. Evidently, there is considerable scatter in the data (the uncertainties in A/D and f_c/f_s are, $\mp$ 3.4% and $\mp$ 5.0% respectively). In spite of this, however, it is apparent, at least for the single Reynolds number under consideration, that the range of synchronization, i.e., $(f_{esr} - f_{bsr})/f_s$, does not strongly depend on A/D. At small values of A/D, the lock-in begins at relatively higher cylinder frequencies, and for A/D larger than approximately 0.5, the synchronization or lock-in begins at about $f_c/f_s = 0.75$. At any rate, it is interesting to note that the desynchronization frequency f_{esr}/f_s is nearly independent of A/D.

Figures 29 and 30 are the plots of Reynolds number versus the limiting cylinder frequencies at the two ends of the synchronization range, namely, f_{bsr}/f_s and f_{esr}/f_s, for two different A/D ratios. The emerging facts from Figs. 28, 29,

and 30 are that the synchronization range, as defined above, does not strongly depend on either A/D or Re within the range of these parameters covered herein and that, if any, the influence of A/D and Re is more on the inception of the synchronization than on its termination.

These results are similar to those of Koopman (8) who did his work in a wind tunnel at Reynolds numbers below 300. However, Bishop and Hassan (1), who did their work with water at a Reynolds number of 6000, showed that the beginning of the synchronization range was displaced further from the Strouhal frequency as A/D increased up to 0.38 and then started moving closer to the Strouhal frequency as A/D was increased further. At A/D = 1, they found the frequency f_{bsr} to be the same as the Strouhal frequency. The differences in the observed effects of the relative amplitude might lie in the fact that Bishop and Hassan did not directly measure the vortex-shedding frequency but instead measured the frequency of the oscillations of the lift force. Notwithstanding these observations and differences in conclusions, it must be evident that the phenomenon is extremely complex and the understanding of even the inception and termination of the synchronization range alone in terms of the parameters so far used is quite incomplete.

Berger and Wille (19) suggested that the relative amplitude is not a separate independent parameter as straightforward dimensional analysis might suggest. In view of this recommendation, several other normalized parameters were considered

and plots were made. Among these, the following appeared to be the most promising. Rewriting Eq. (a) as

$$f_v = F\left(A, D, V, f_c, \rho, \mu\right)$$

and normalizing anew for the cases where $f_v = f_c$, one has

$$\frac{Af_c}{V} = F\left(\frac{Af_s}{V}, Re, \frac{A}{D}\right)$$

the variation of Af_c/V with Af_s/V for all values of A/D listed in Table I and the Reynolds numbers from 435 to 1750 is shown in Fig. 31. The obvious fact is that Af_c/V and Af_s/V variation does not significantly depend on either A/D or Re, as stated earlier and that the inception of synchronization is a relatively more complex non-linear phenomenon than the occurrence of desynchronization. Additional conjectures may be made on the basis of this or similar graphs proposed by others during the past decade but no additional conclusions can be drawn without a detailed analysis of the kinematics of the time-dependent fluid motion.

The data obtained with the freely oscillating cylinder are presented in Fig. 32. It is observed that when $f_s << f_n$, the amplitude of the cylinder oscillations is relatively small and the cylinder frequency cannot be determined with sufficient degree of accuracy. In this range the vortex shedding frequency was equal to the Strouhal frequency. As the velocity of the flow was increased until a state was reached at which $f_s = 0.84\ f_n$, the amplitude of the oscillations jumped to 0.75 inches, i.e., A/D = 1, and the cylinder

and vortex-shedding frequencies became synchronized. The common frequency was above the Strouhal frequency. This state marked the inception of the synchronization range. As the velocity was further increased, f_v remained equal to f_c, and both remained nearly equal to f_n. The amplitude of the oscillation increased until $f_s \simeq 1.32\ f_n$. Eventually, the amplitude gradually decreased. Ferguson and Parkinson (2) suggested that this is the result of the rapid phase shift observed between the lift and displacement over the velocity range of synchronization. Limitations of the test apparatus precluded the possibility of increasing the velocities to the point where the amplitude of the cylinder oscillations dropped to a very small value as in the experiments by Meier-Windhorst (6).

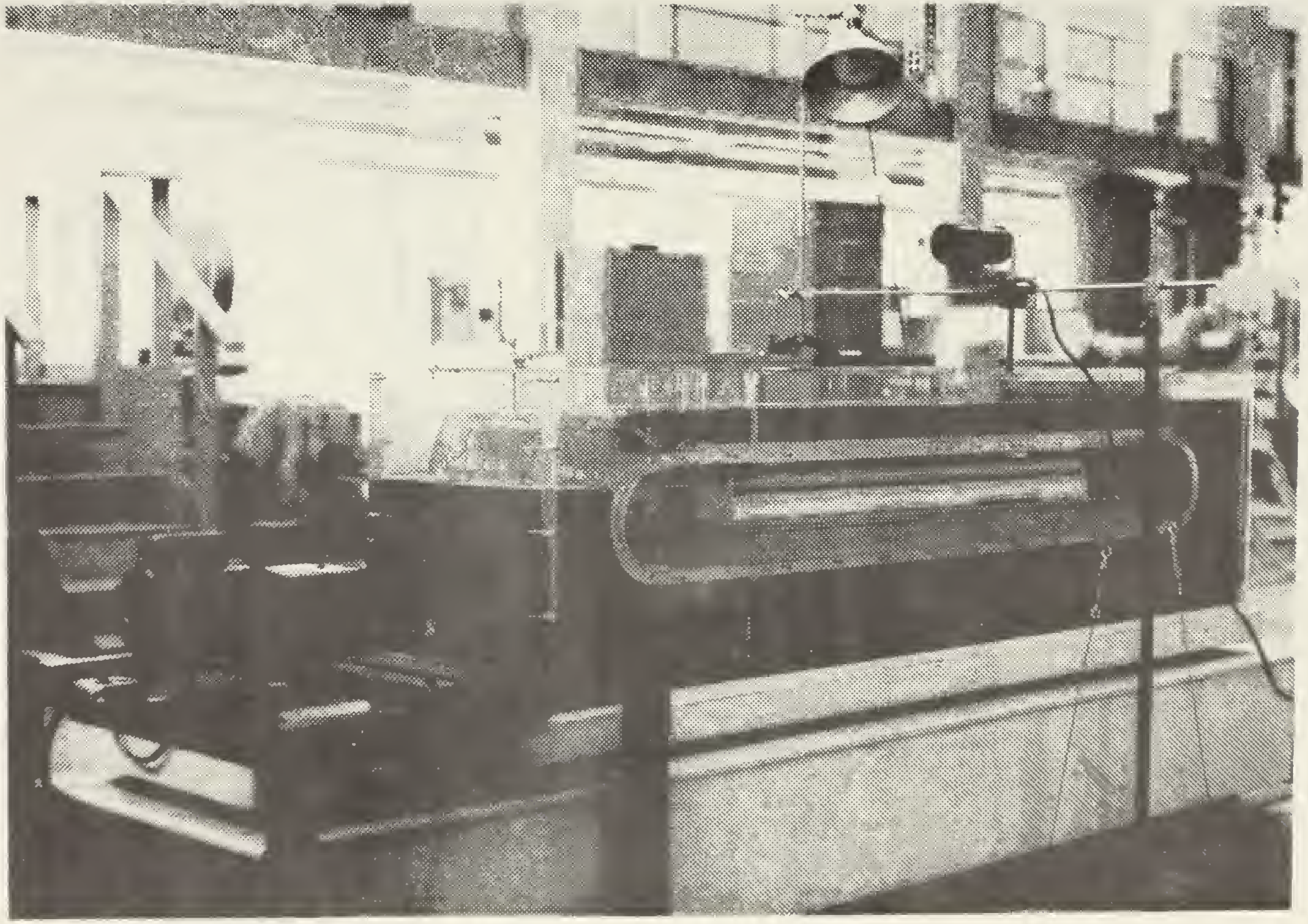
An interesting comparison can be made between the characteristics of the forced and free oscillations of the cylinder. Defining once again the synchronization range as $f_c = f_v$, calculating the parameters $A_f c/V$ and Af_s/V for the case of free oscillations, and plotting them on Fig. 31, it is noted that the free oscillation data fit very well with the forced oscillation data. Although helpful, this is not a result of major consequence since in the case of free oscillations the amplitude is not an independent parameter and since there is, among other things, a phase shift in the relationship between the vortex shedding and the oscillation of the structure within the synchronization range (1, 2).

IV. CONCLUSIONS

The present investigation dealt primarily with the forced oscillations of circular cylinders in water in a direction transverse to the flow and to a limited extent with the free oscillations of a cylinder. In either case a "lock-in" or frequency synchronization range has been observed in a manner similar to that previously observed by others at much smaller Reynolds numbers. It has been shown that the range of synchronization is weakly dependent upon A/D and Re and that it can be fairly well predicted in terms of Af_c/V and Af_s/V.

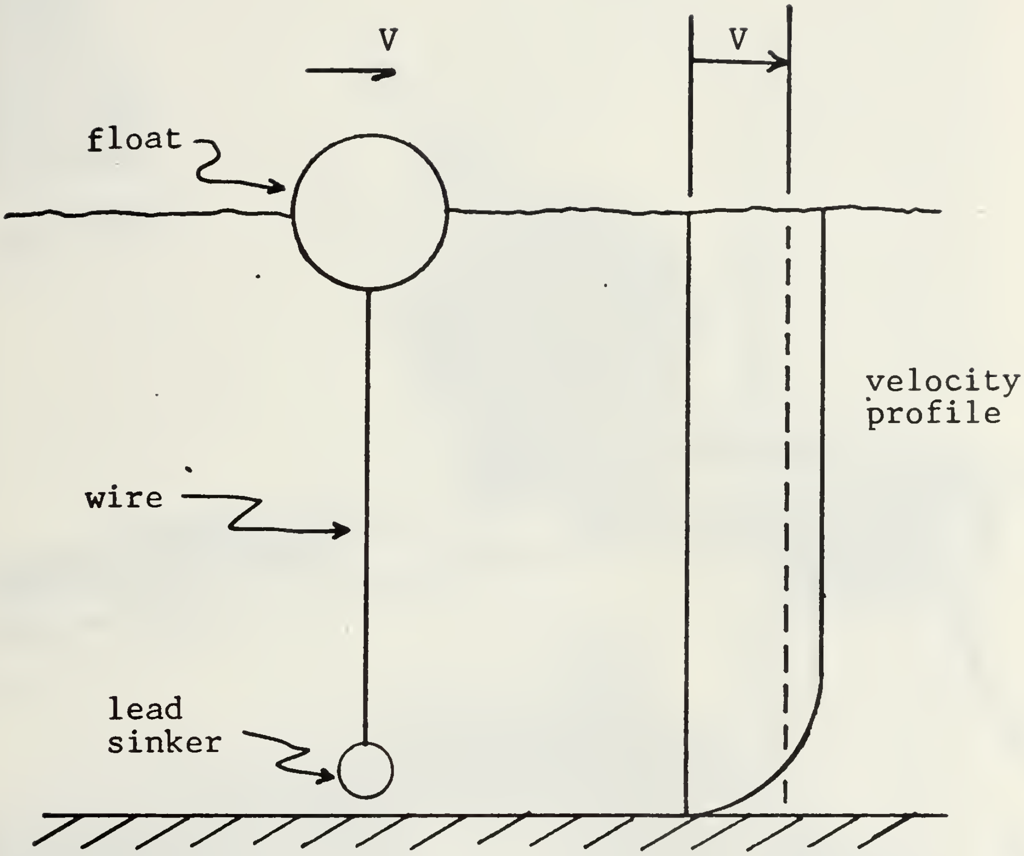
In the case of free oscillations, as the velocity of flow was gradually increased, with corresponding increase of the Strouhal frequency f_s for the stationary cylinder, oscillations of the cylinder begin when f_s is only slightly less than the natural frequency f_n of the cylinder. At a critical velocity, the frequency f_s becomes nearly equal to f_n and the amplitude of the oscillation continues to increase with the velocity of flow up to about 1.32 f_nD/S. Eventually, the amplitude of the oscillations decrease.

A combination of the conclusions of this exploratory investigation with those obtained by others suggests that further progress on this phenomenon will come not from additional laboratory experiments but most likely from new numerical experiments through the use of the discrete vortex model.



Free Surface Channel

Figure 1

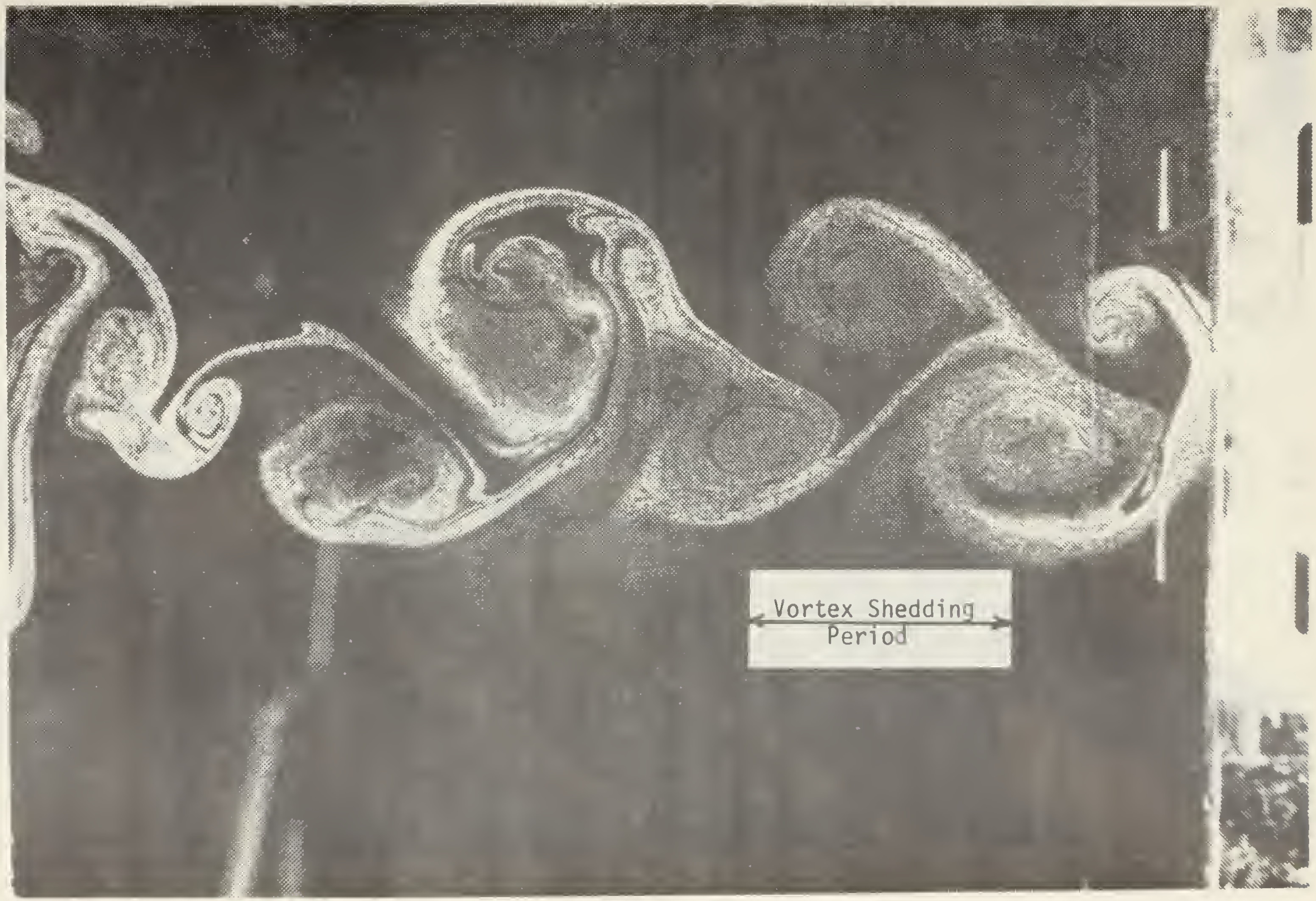


Velocity Float Assemble

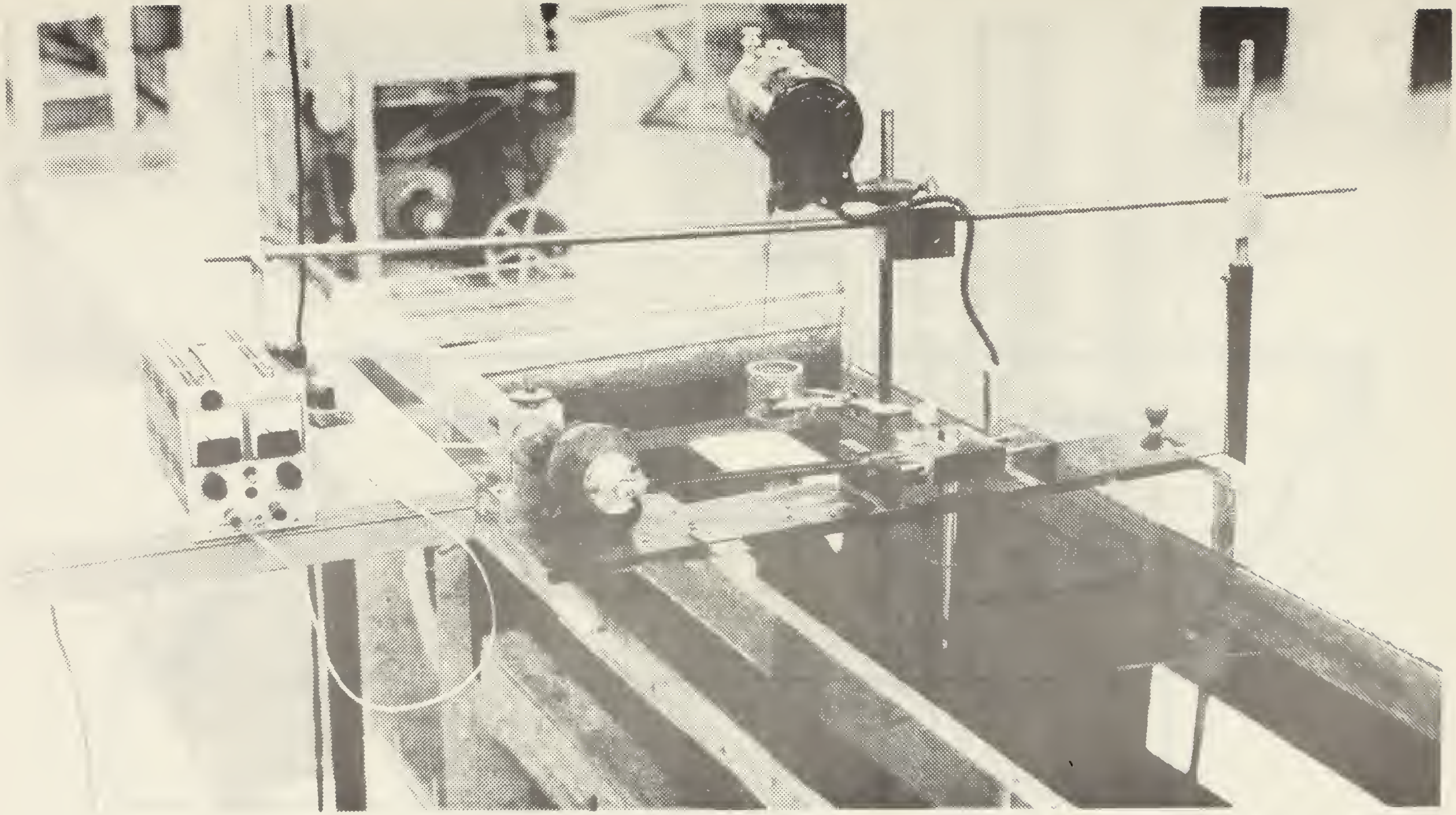
Figure 2

Powder Dispenser

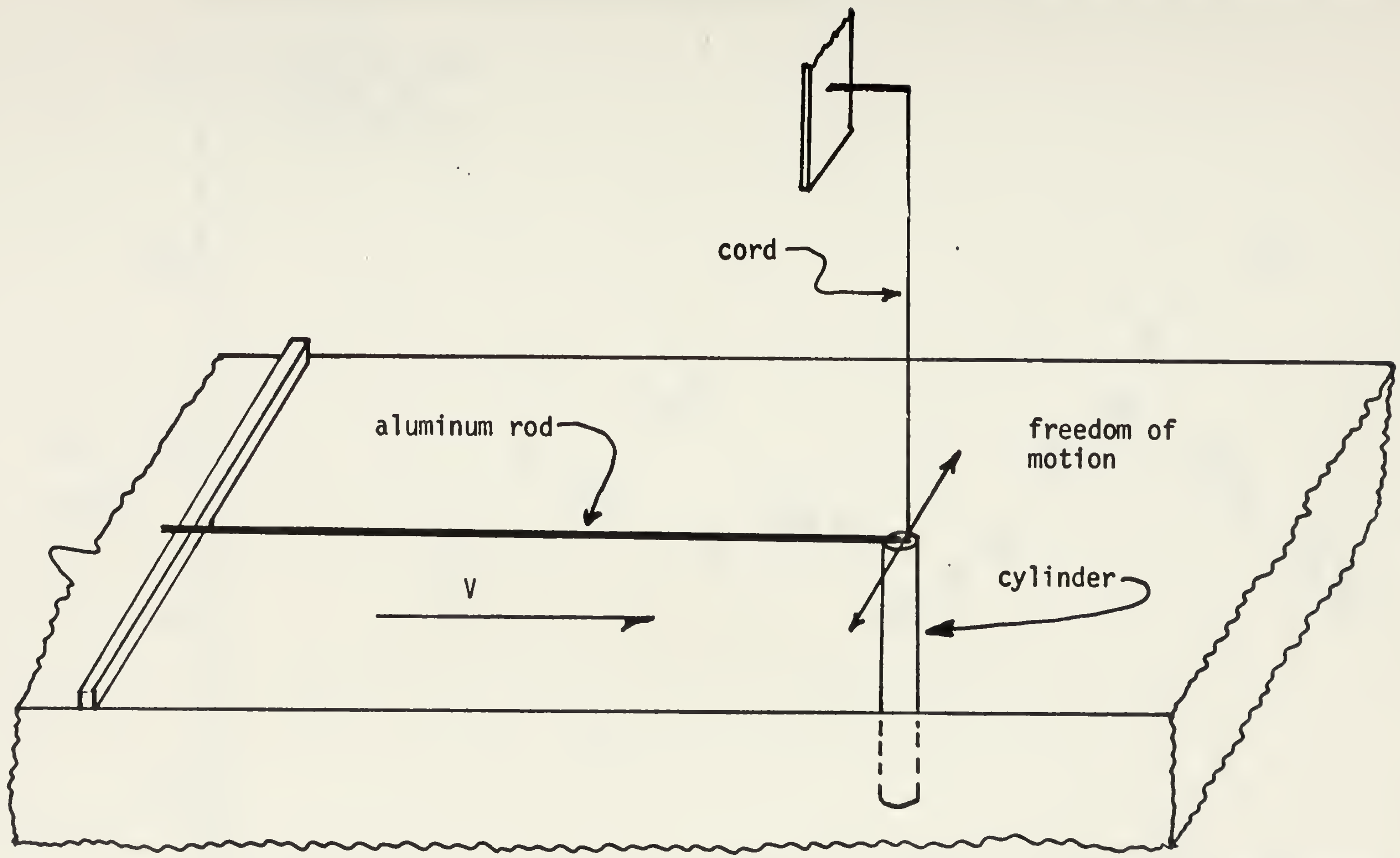
Figure 3



Vortex Shedding Period
Figure 4

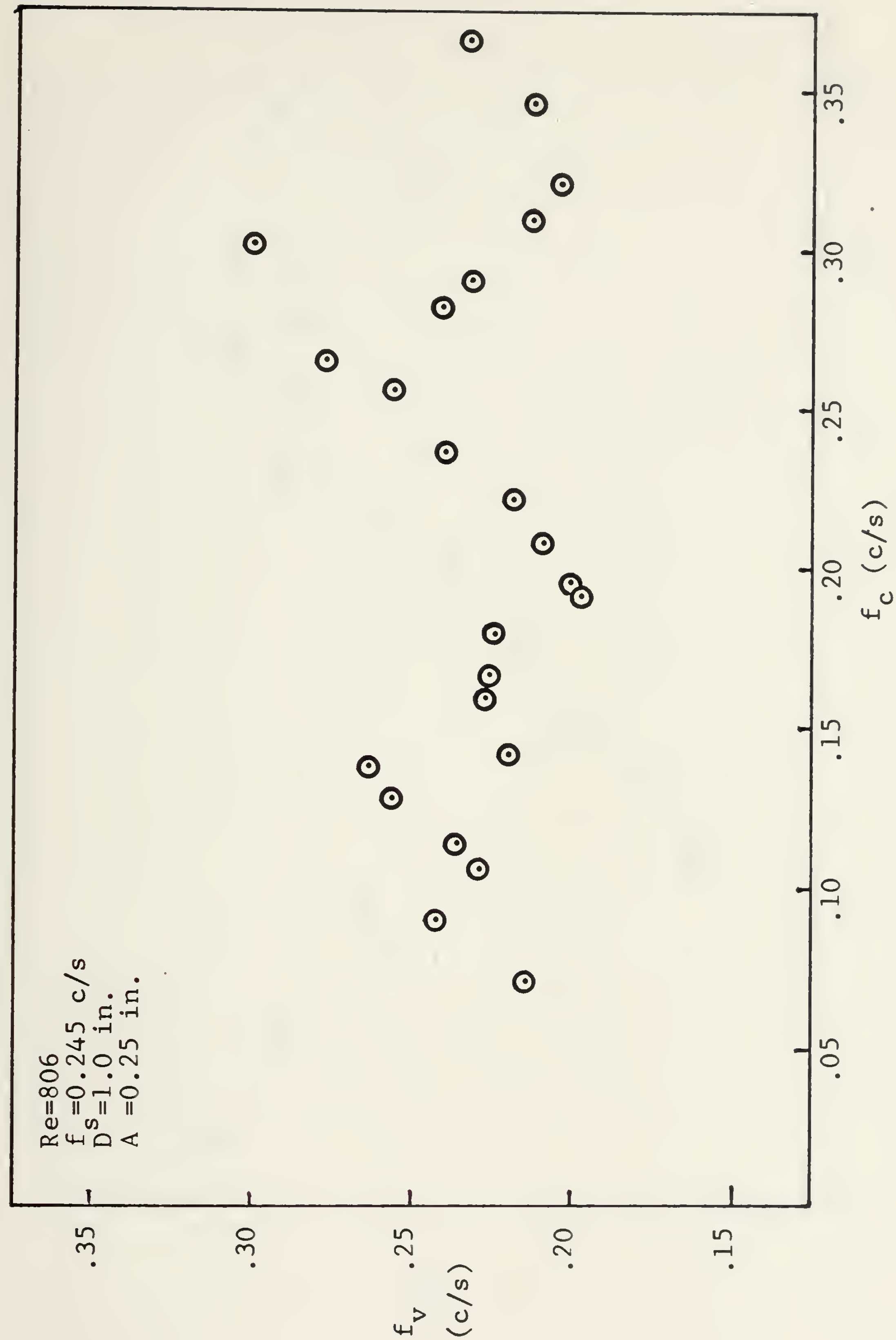


Cylinder Oscillation Assembly
Figure 5



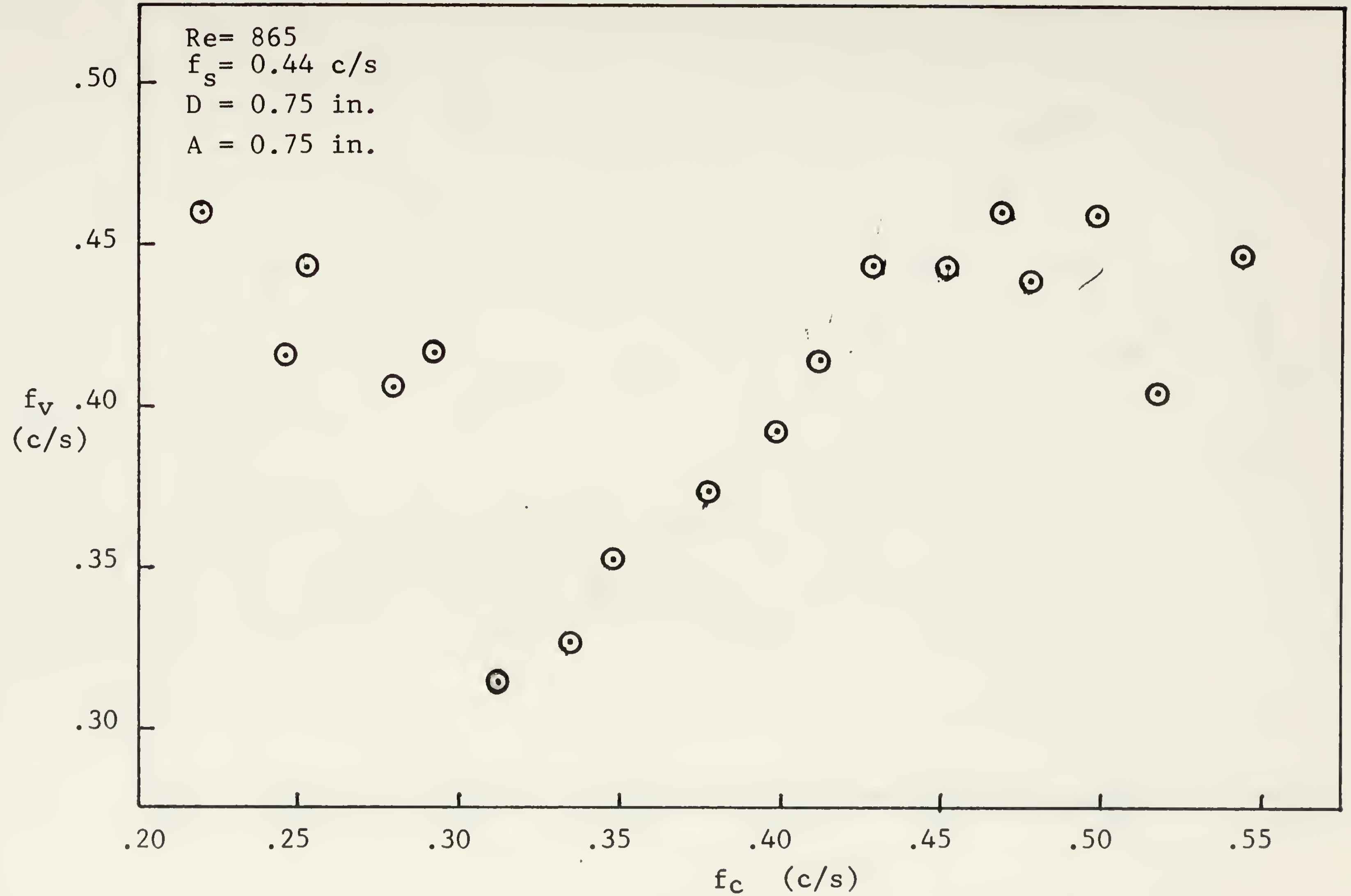
Free Oscillation Assembly

Figure 6



Re=806
f =0.245 c/s
Ds=1.0 in.
A =0.25 in.
.35
.30
.25
.20
.15
fv
(c/s)
.05
.10
.15
.20
.25
.30
.35
fc (c/s)

Figure 7



Re= 865
f_s= 0.44 c/s
D = 0.75 in.
A = 0.75 in.
.50
.45
f_v .40
(c/s)
.35
.30
.20
.25
.30
.35
.40
.45
.50
.55
f_c (c/s)

Figure 8

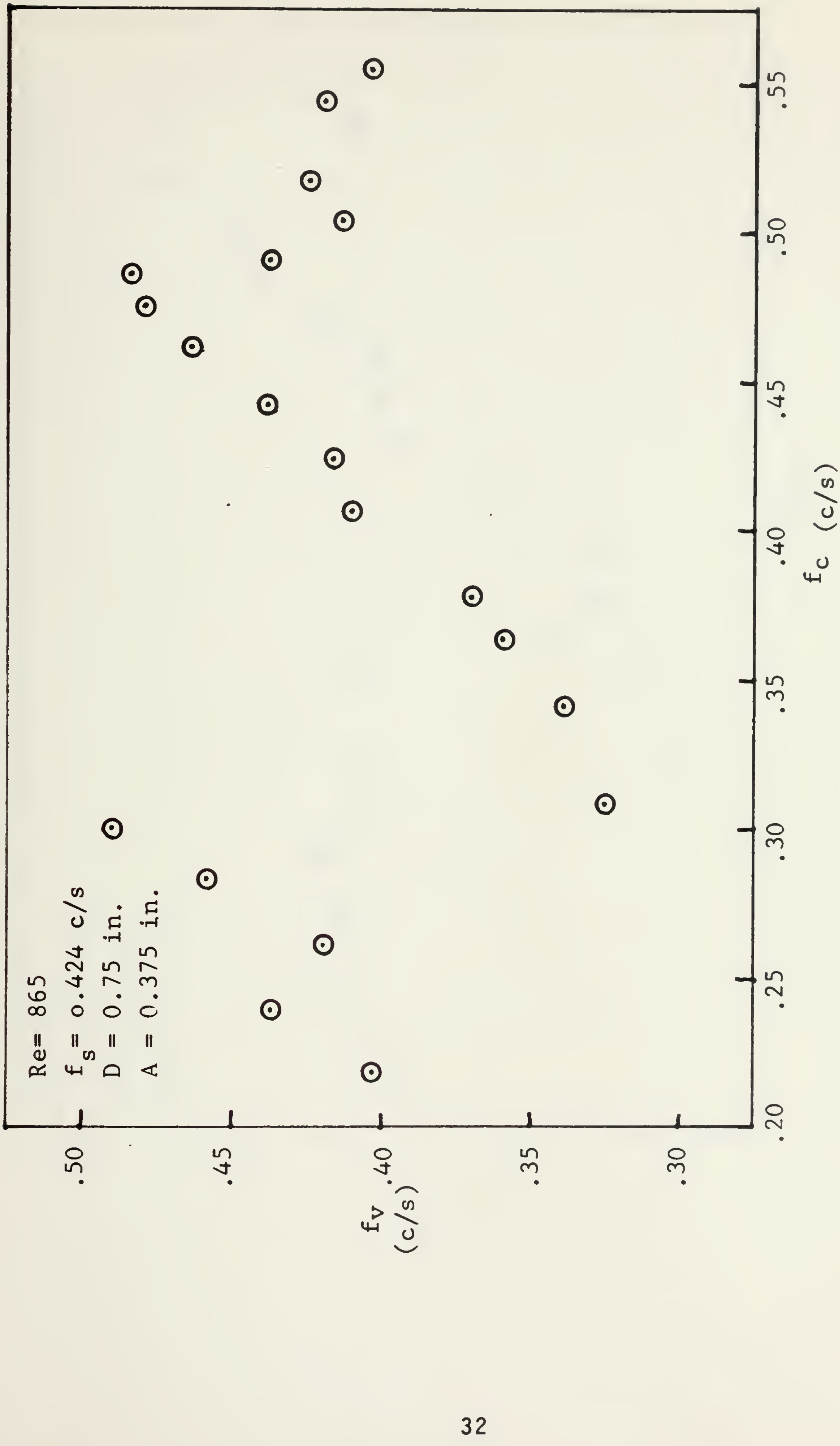
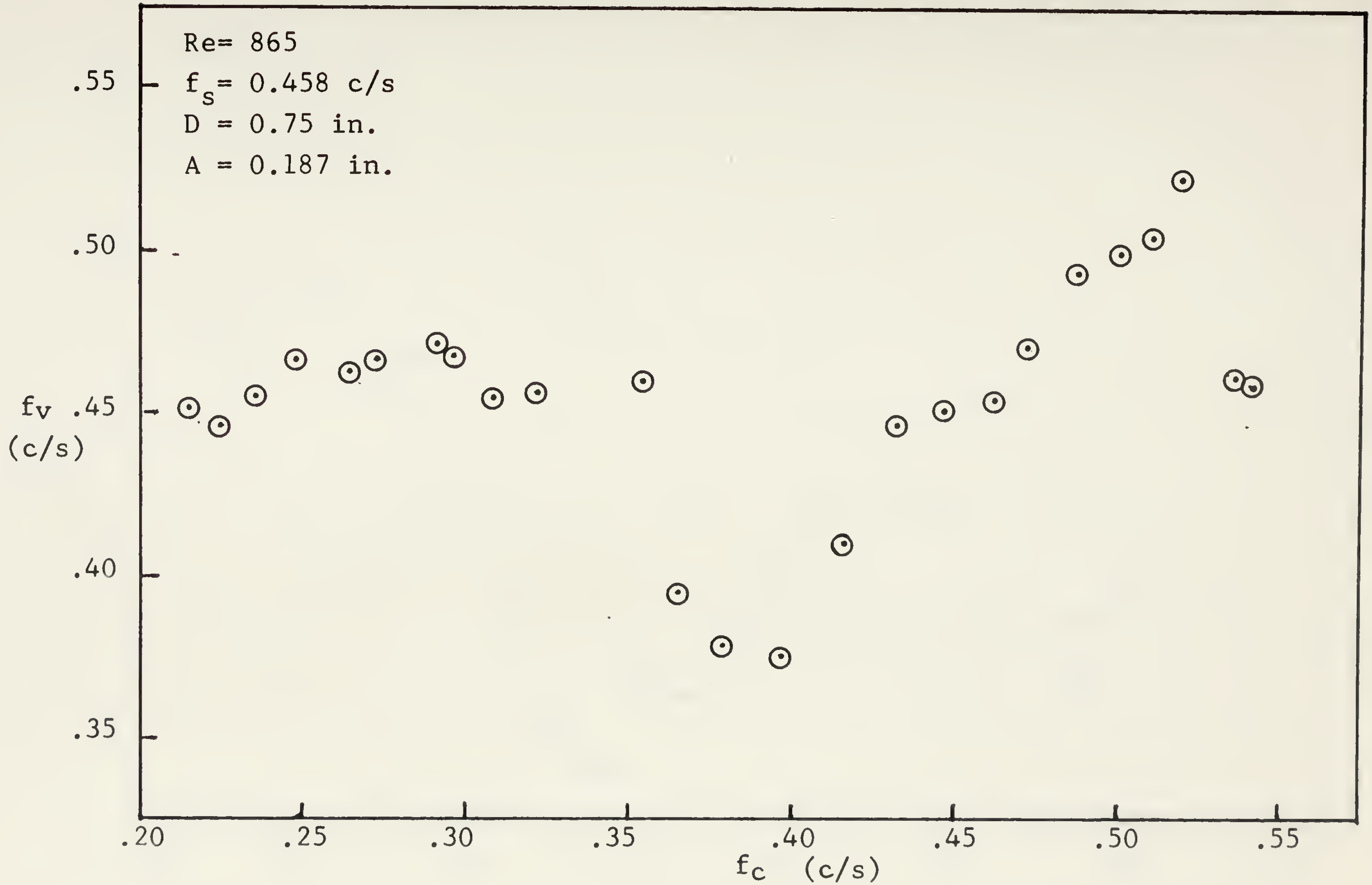
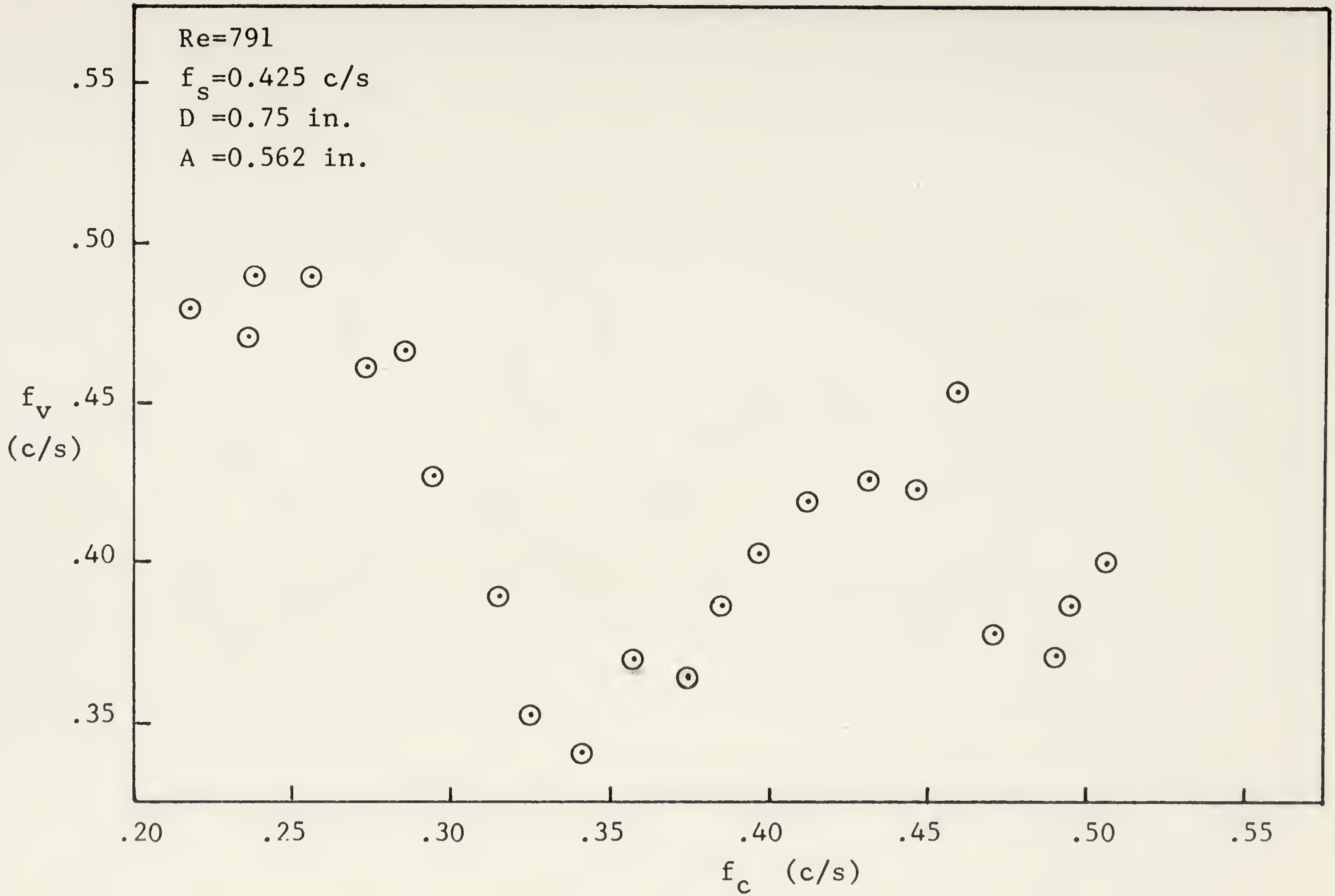

Re= 865
f_s= o.424 c/s
D = 0.75 in.
A = 0.375 in.
.50
.45
.40
.35
.30
f_v (c/s)
.20
.25
.30
.35
.40
.45
.50
.55
f_c (c/s)

Figure 9



Re= 865
f_s= 0.458 c/s
D = 0.75 in.
A = 0.187 in.
.55
.50
f_v .45
(c/s)
.40
.35
.20
.25
.30
.35
.40
.45
.50
.55
f_c (c/s)

Figure 10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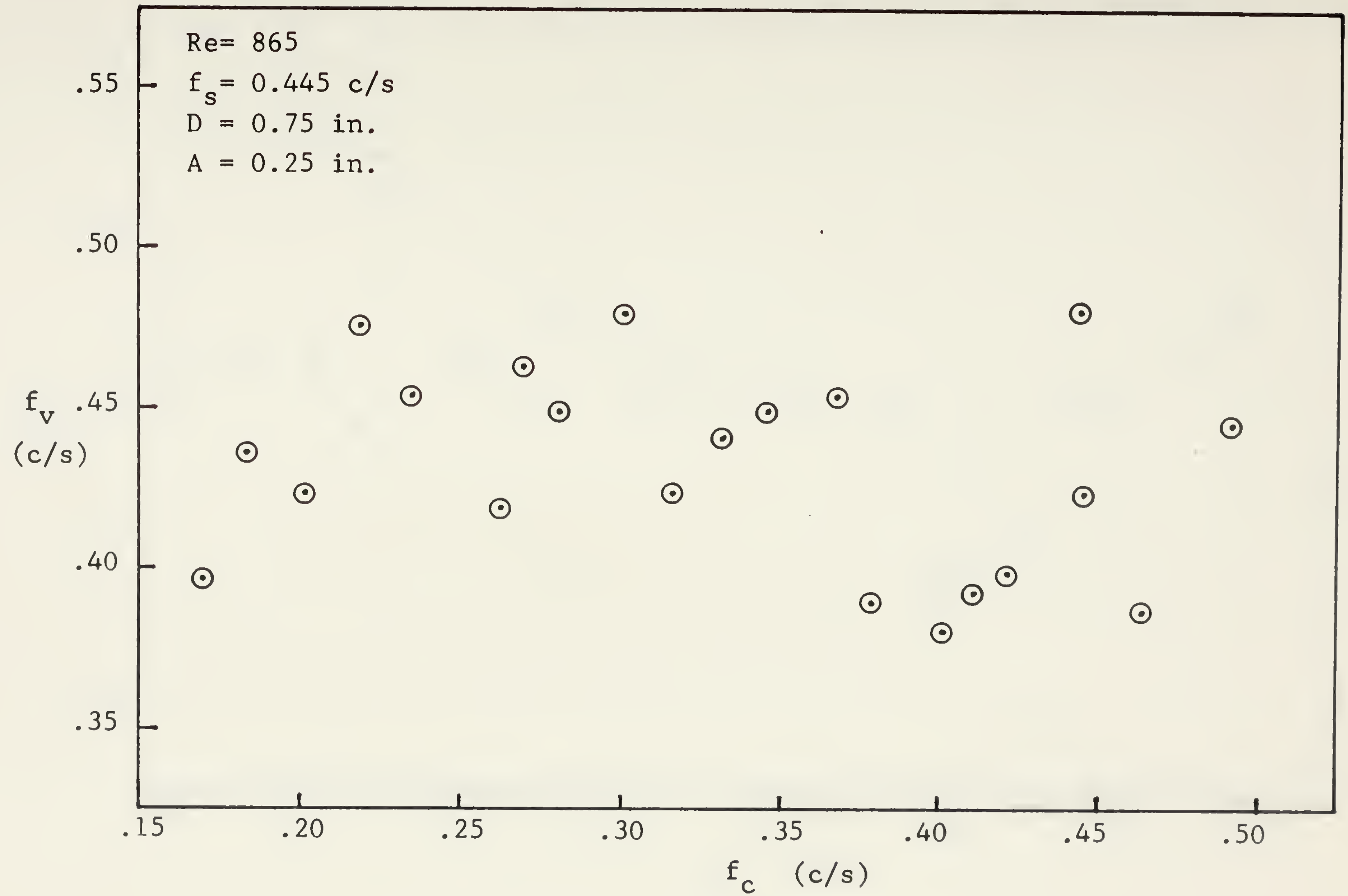
f s=0.425 c/s
D =0.75 in.
A =0.562 in.
.55
.50
f v .45
(c/s)
.40
.35
.20
.25
.30
.35
.40
.45
.50
.55
f c (c/s)

Figure 11



Re= 865
f_s= 0.445 c/s
D = 0.75 in.
A = 0.25 in.
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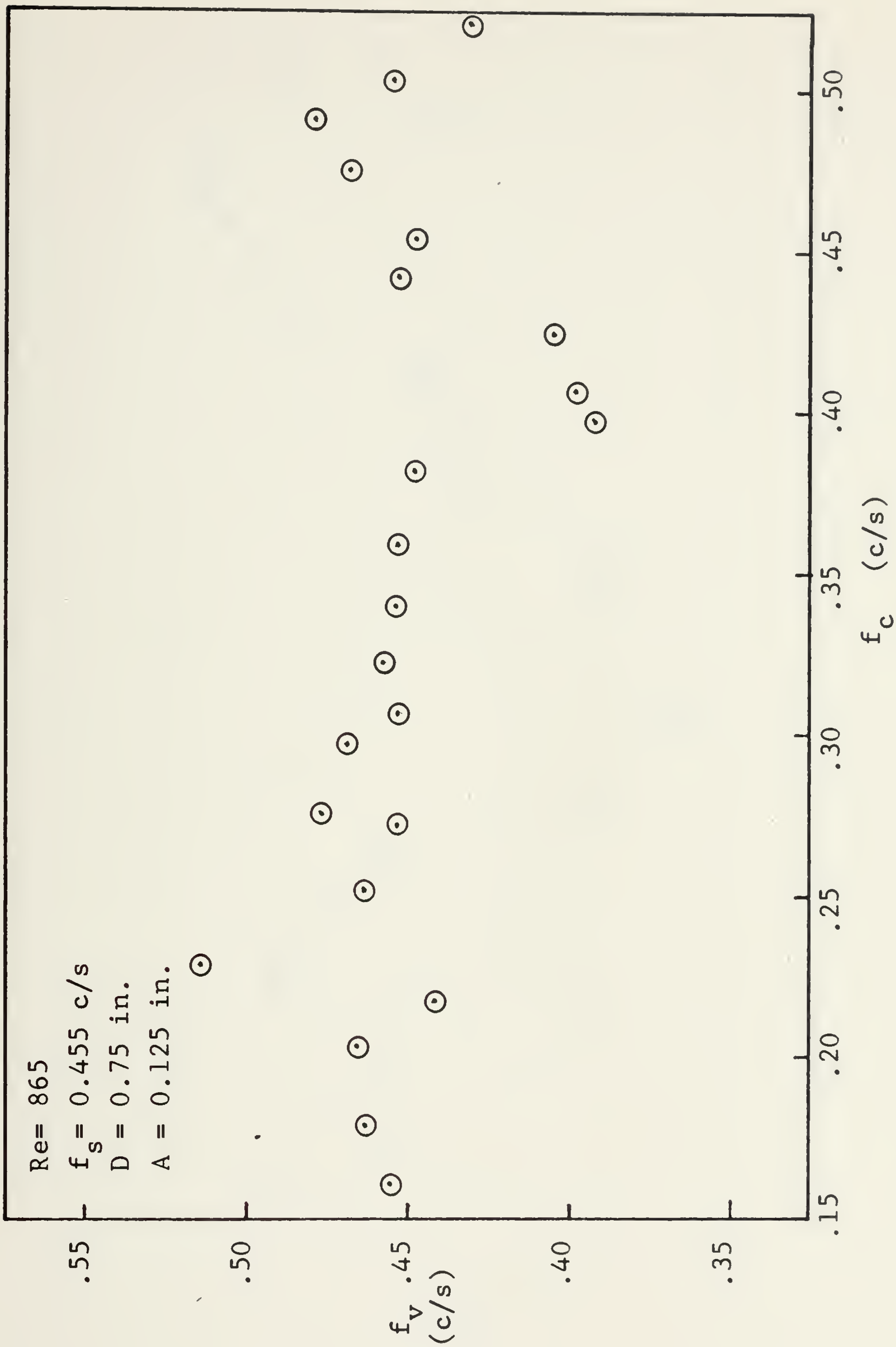
.50
f_v .45
(c/s)
.40
.35
.15
.20
.25
.30
.35
.40
.45
.50
f_c (c/s)

Figure 12



Re= 865
f_s= 0.455 c/s
D = 0.75 in.
A = 0.125 in.
f_v (c/s)
.55
.50
.45
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.35
.15
.20
.25
.30
.35
.40
.45
.50
f_c (c/s)

Figure 13

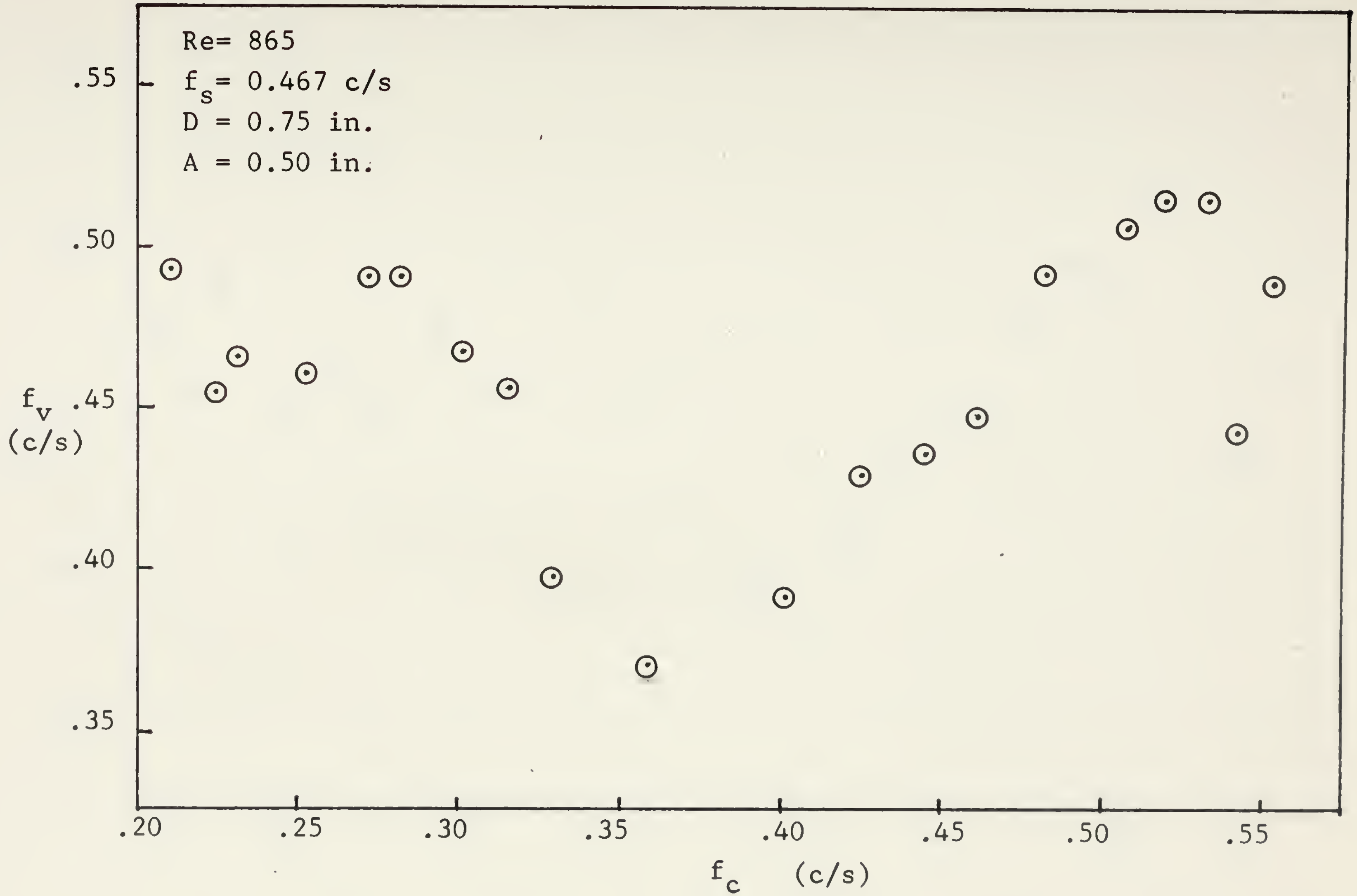
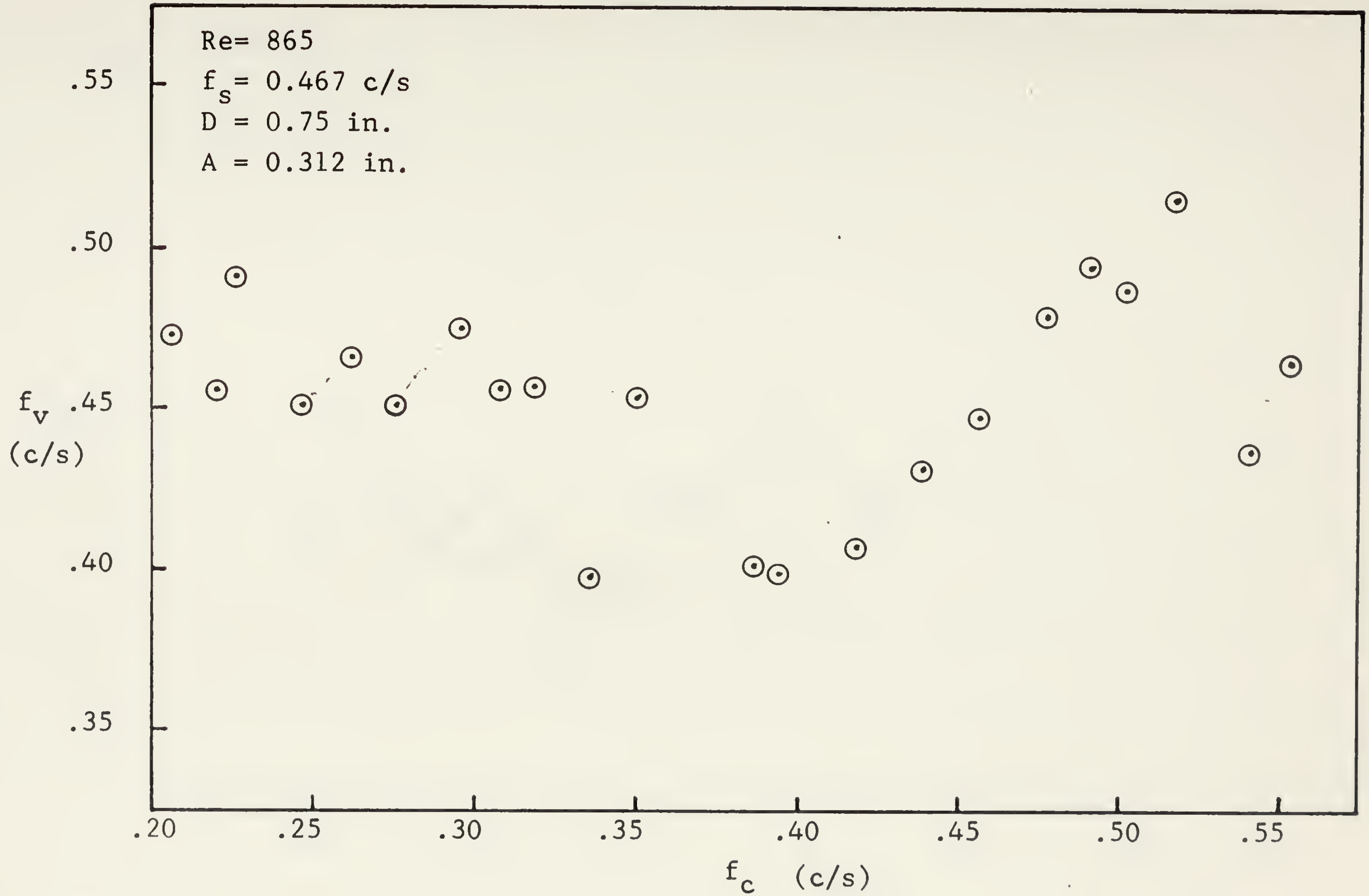
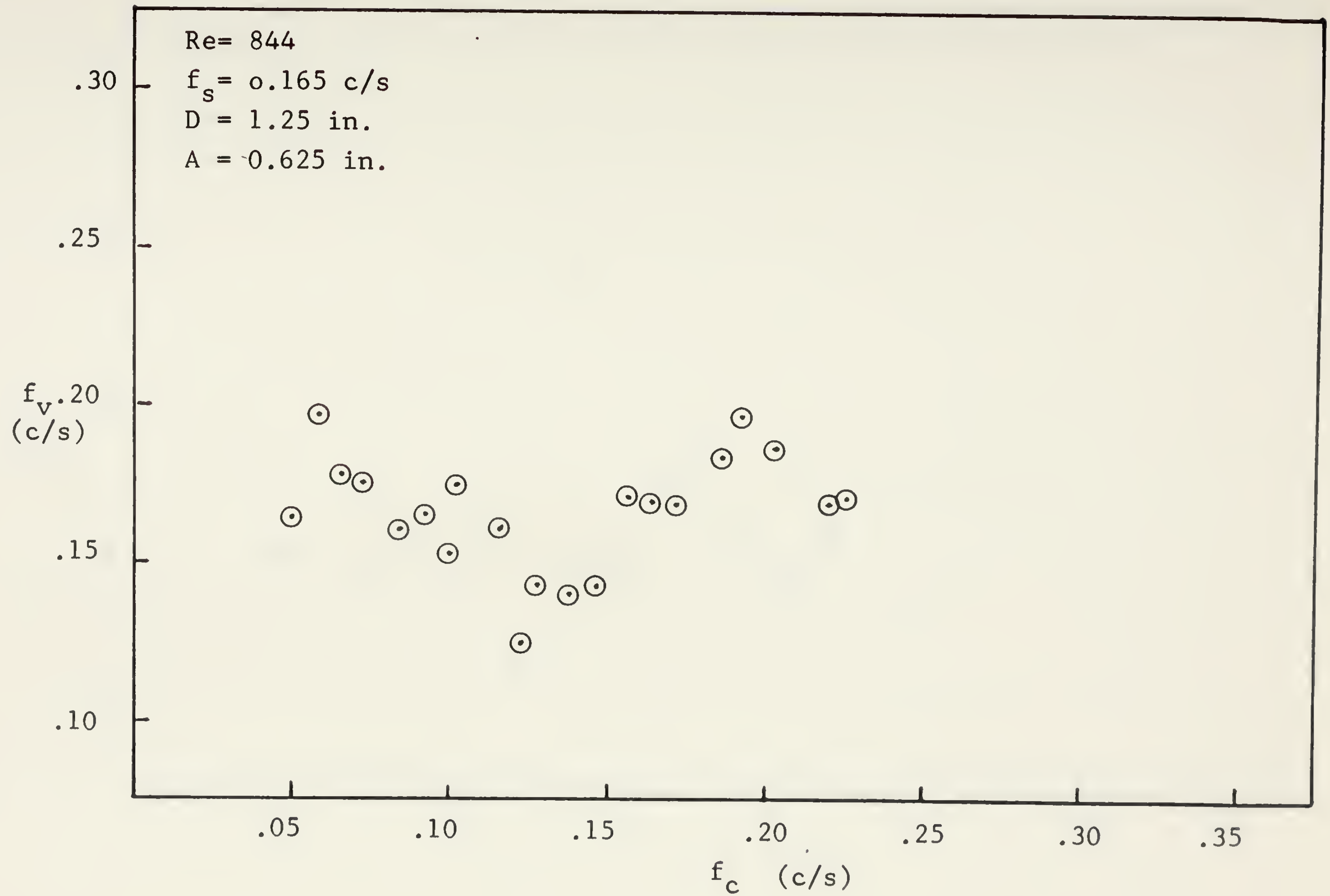

Re= 865
f_s= 0.467 c/s
D = 0.75 in.
A = 0.50 in.
.55
.50
f_v .45
(c/s)
.40
.35
.20
.25
.30
.35
.40
.45
.50
.55
f_c (c/s)

Figure 14



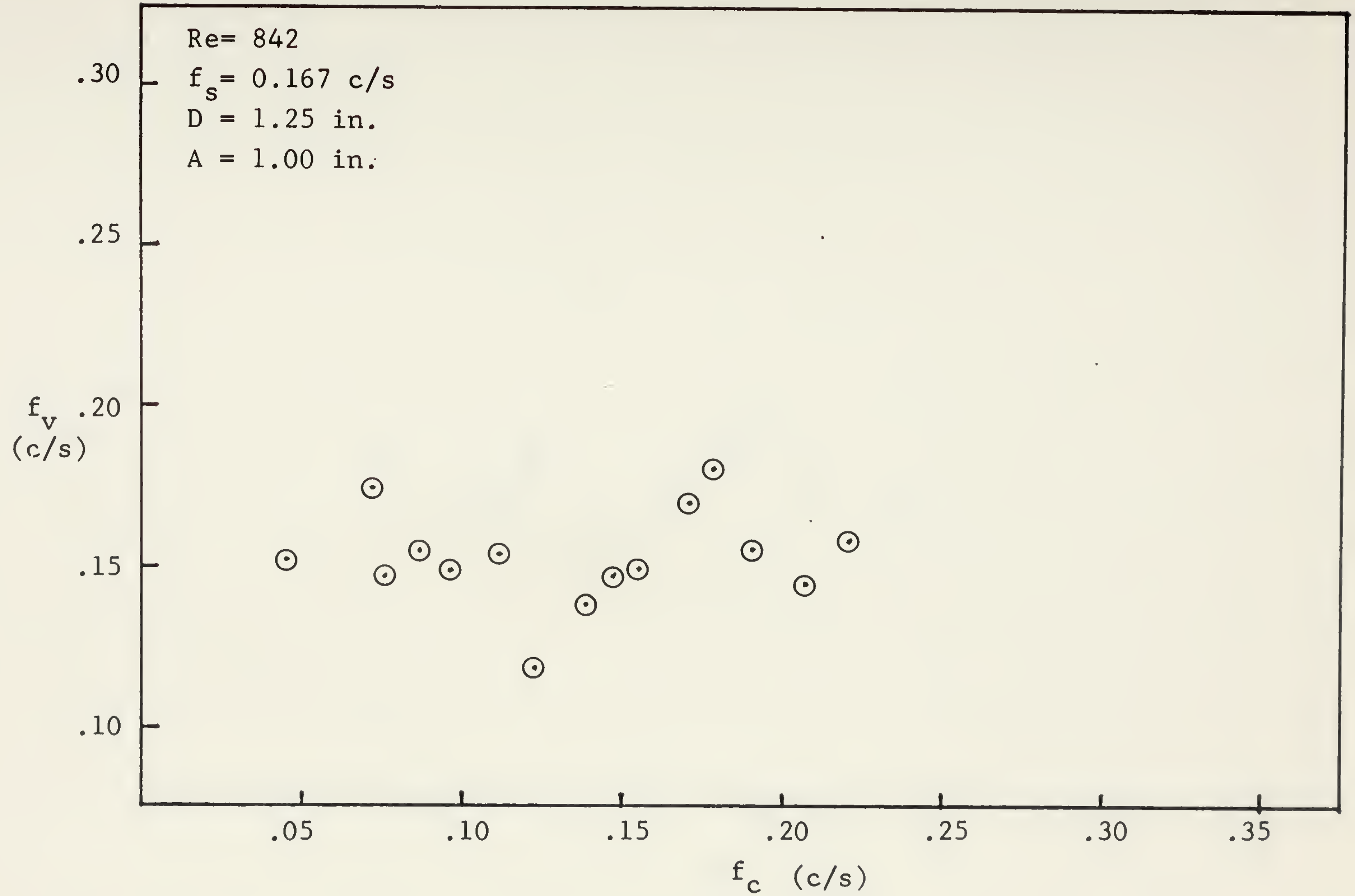
Re= 865
f_s= 0.467 c/s
D = 0.75 in.
A = 0.312 in.
.55
.50
f_v .45
(c/s)
.40
.35
.20
.25
.30
.35
.40
.45
.50
.55
f_c (c/s)

Figure 15



Re= 844
f_s= o.165 c/s
D = 1.25 in.
A = 0.625 in.
.30
.25
f_v .20
(c/s)
.15
.10
.05
.10
.15
.20
.25
.30
.35
f_c (c/s)

Figure 16



Re= 842
f_s= 0.167 c/s
D = 1.25 in.
A = 1.00 in.
.30
.25
.20
.15
.10
f_v (c/s)
.05
.10
.15
.20
.25
.30
.35
f_c (c/s)

Figure 17

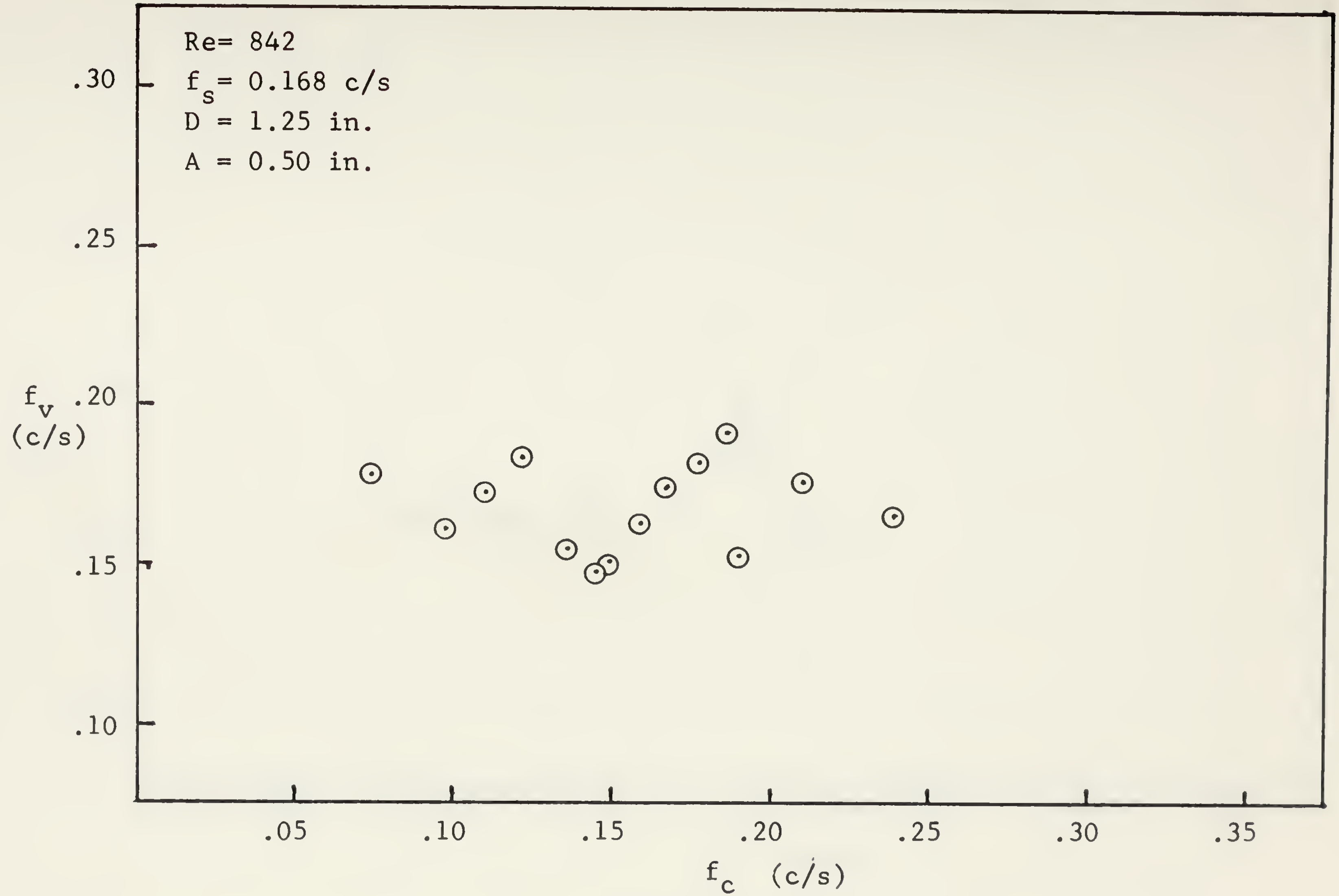

Re= 842
f_s= 0.168 c/s
D = 1.25 in.
A = 0.50 in.
.30
.25
f_v .20
(c/s)
.15
.10
.05
.10
.15
.20
.25
.30
.35
f_c (c/s)

Figure 18

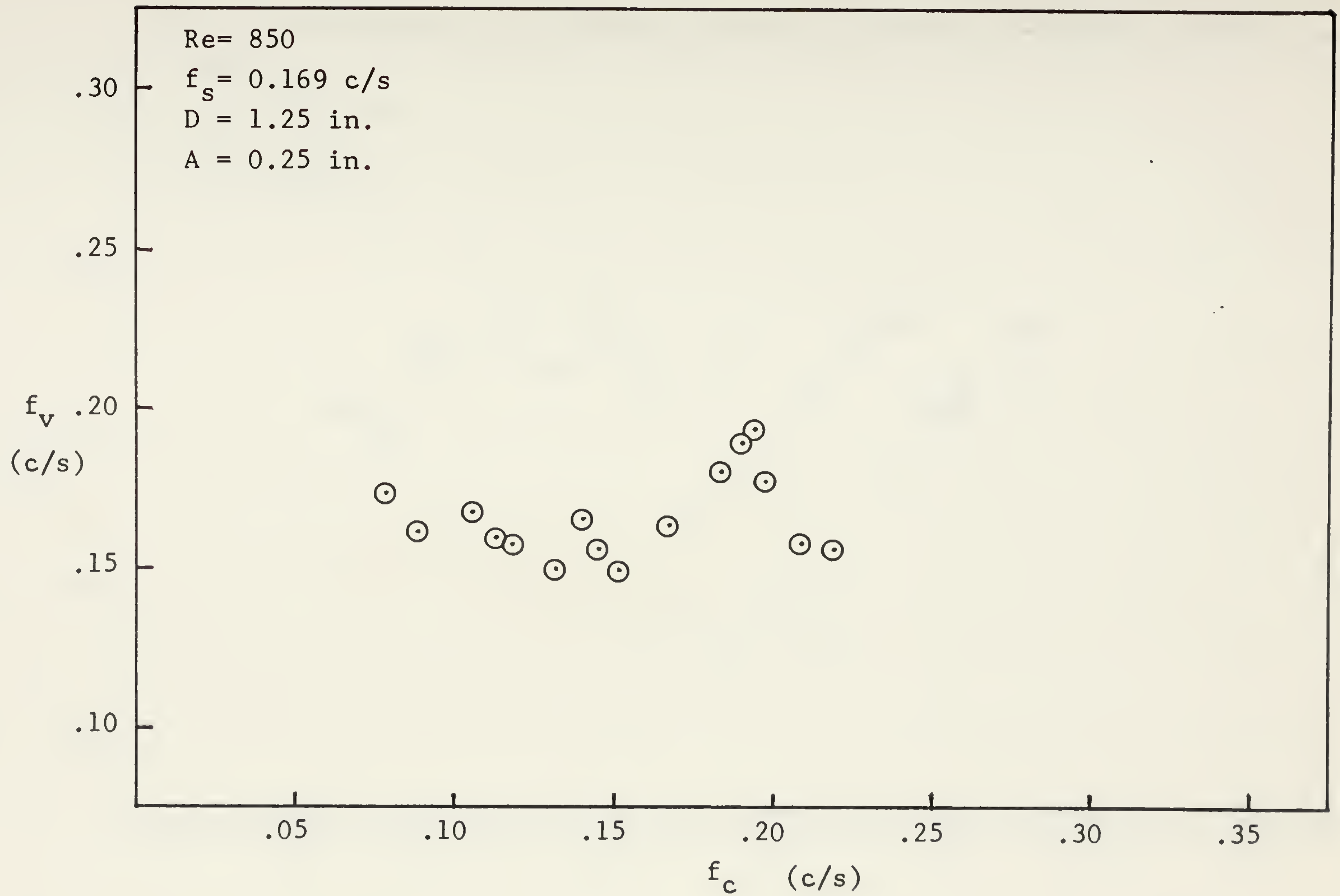

Re= 850
f_s= 0.169 c/s
D = 1.25 in.
A = 0.25 in.
.30
.25
f_v .20
(c/s)
.15
.10
.05
.10
.15
.20
.25
.30
.35
f_c (c/s)

Figure 19

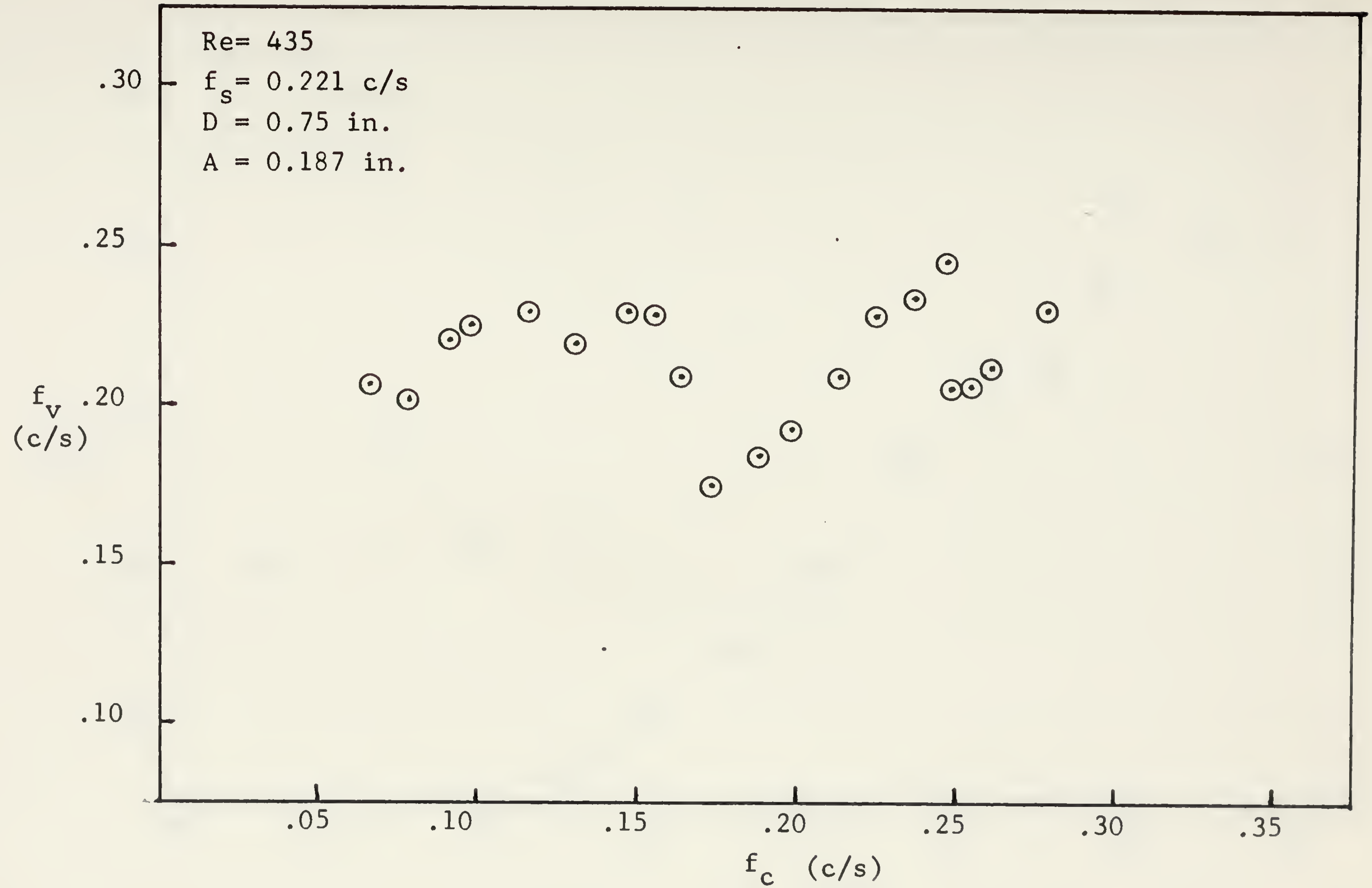
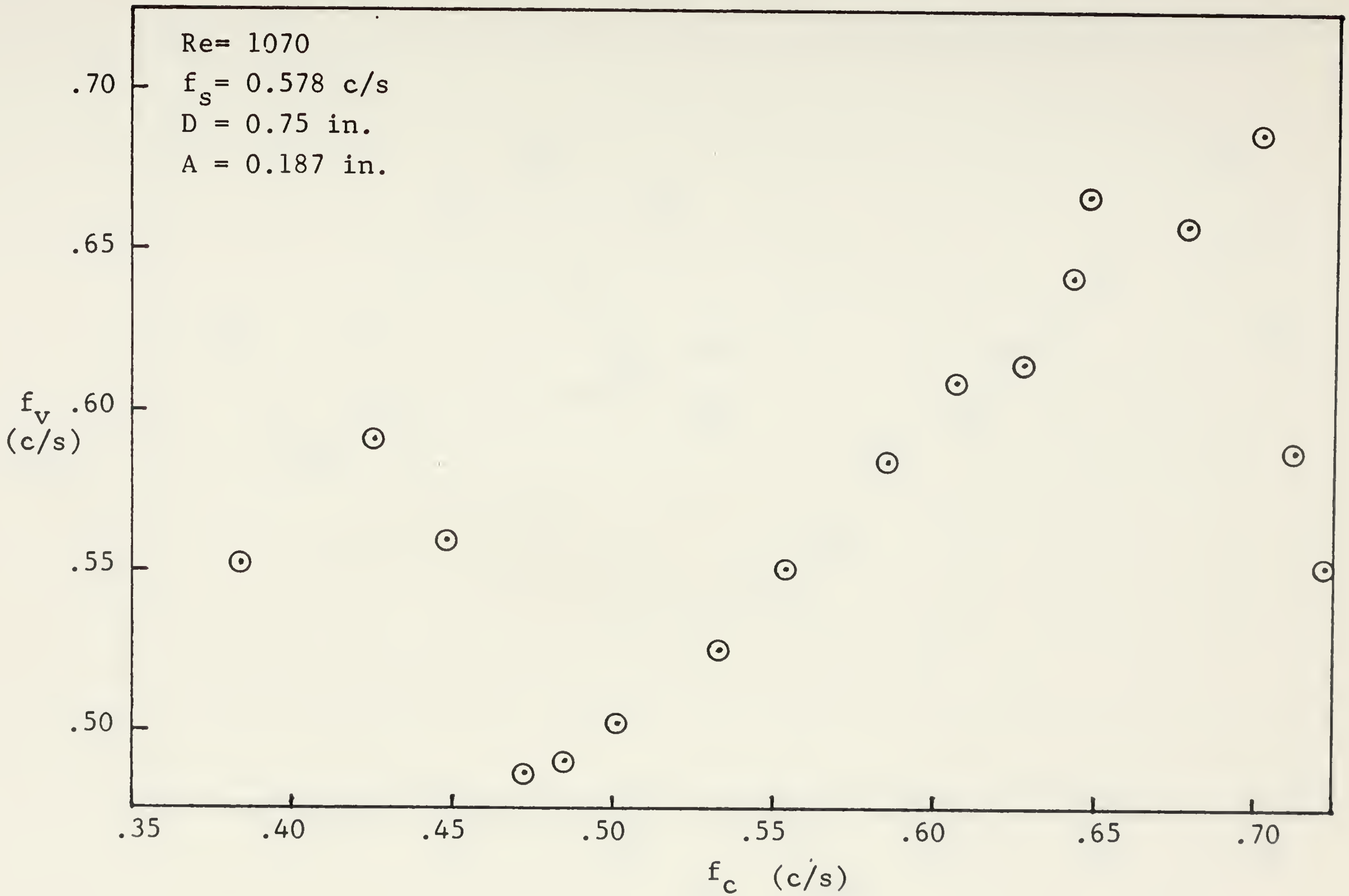

Re= 435
f_s= 0.221 c/s
D = 0.75 in.
A = 0.187 in.
.30
.25
f_v .20
(c/s)
.15
.10
.05
.10
.15
.20
.25
.30
.35
f_c (c/s)

Figure 20



Re= 1070
f s= 0.578 c/s
D = 0.75 in.
A = 0.187 in.
.70
.65
f v .60
(c/s)
.55
.50
.35
.40
.45
.50
.55
.60
.65
.70
f c (c/s)

Figure 21

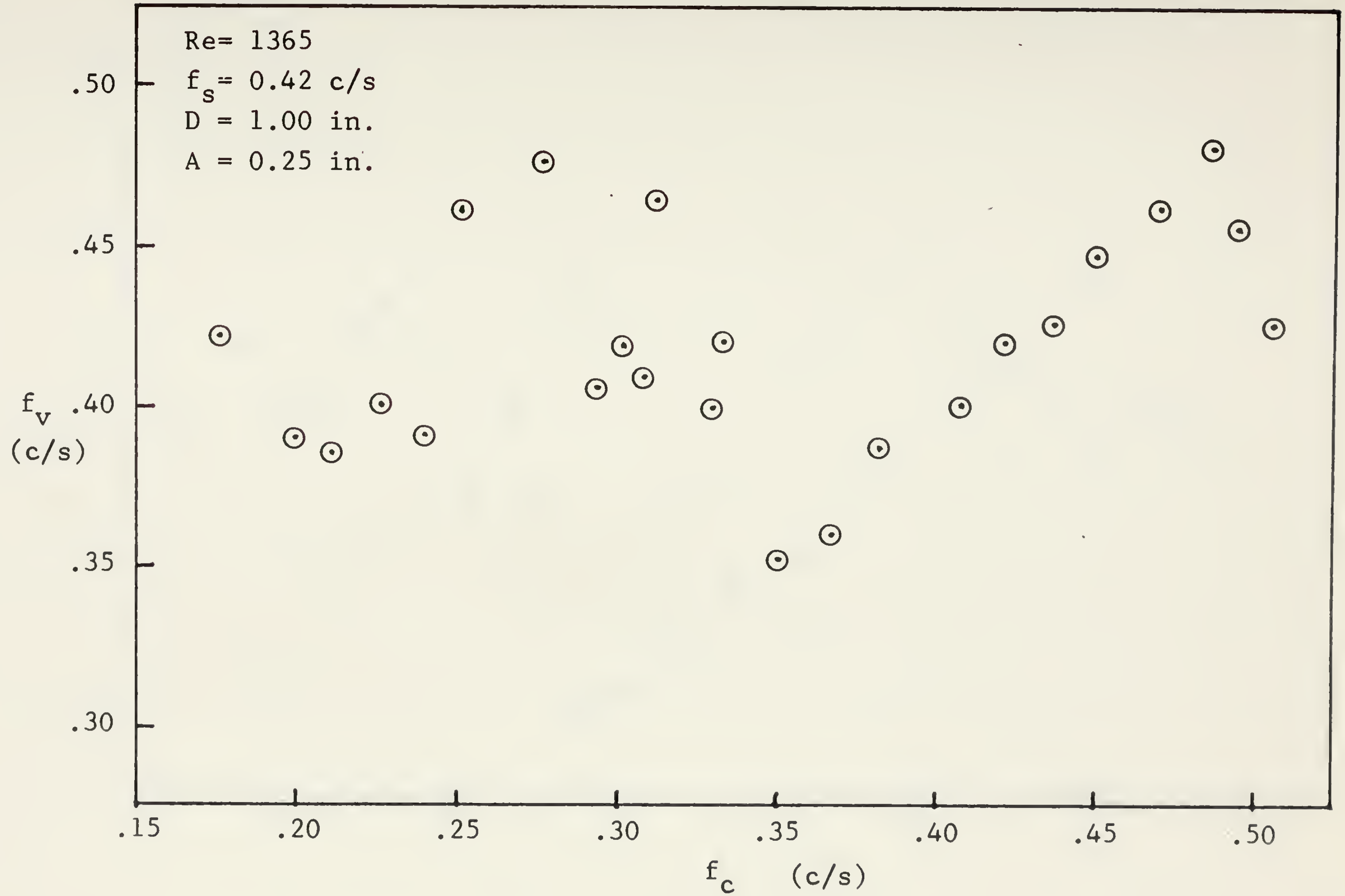
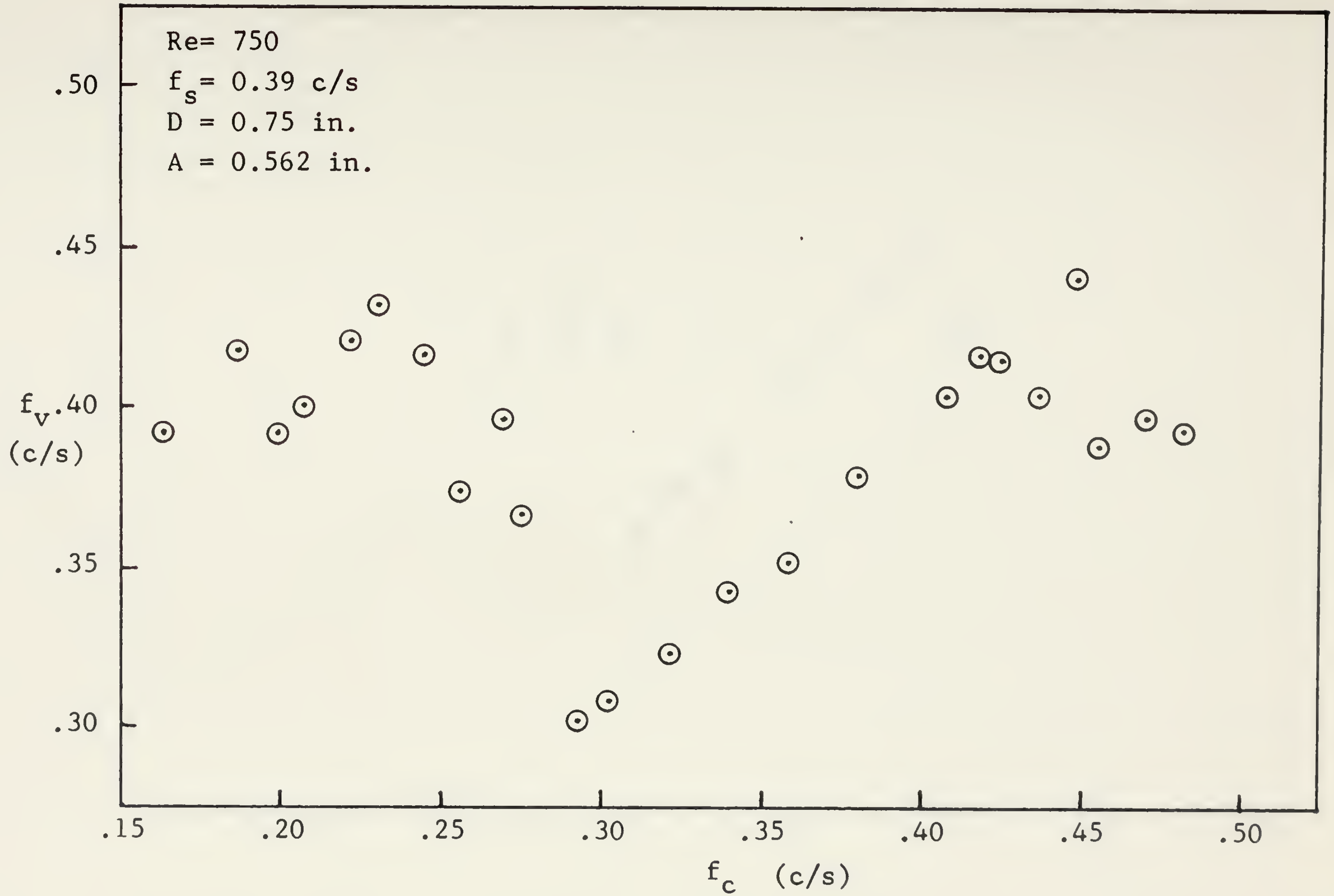

Re= 1365
f_s= 0.42 c/s
D = 1.00 in.
A = 0.25 in.
.50
.45
f_v .40
(c/s)
.35
.30
.15
.20
.25
.30
.35
.40
.45
.50
f_c (c/s)

Figure 22



Re= 750
f_s= 0.39 c/s
D = 0.75 in.
A = 0.562 in.
.50
.45
f_v .40
(c/s)
.35
.30
.15
.20
.25
.30
.35
.40
.45
.50
f_c (c/s)

Figure 23

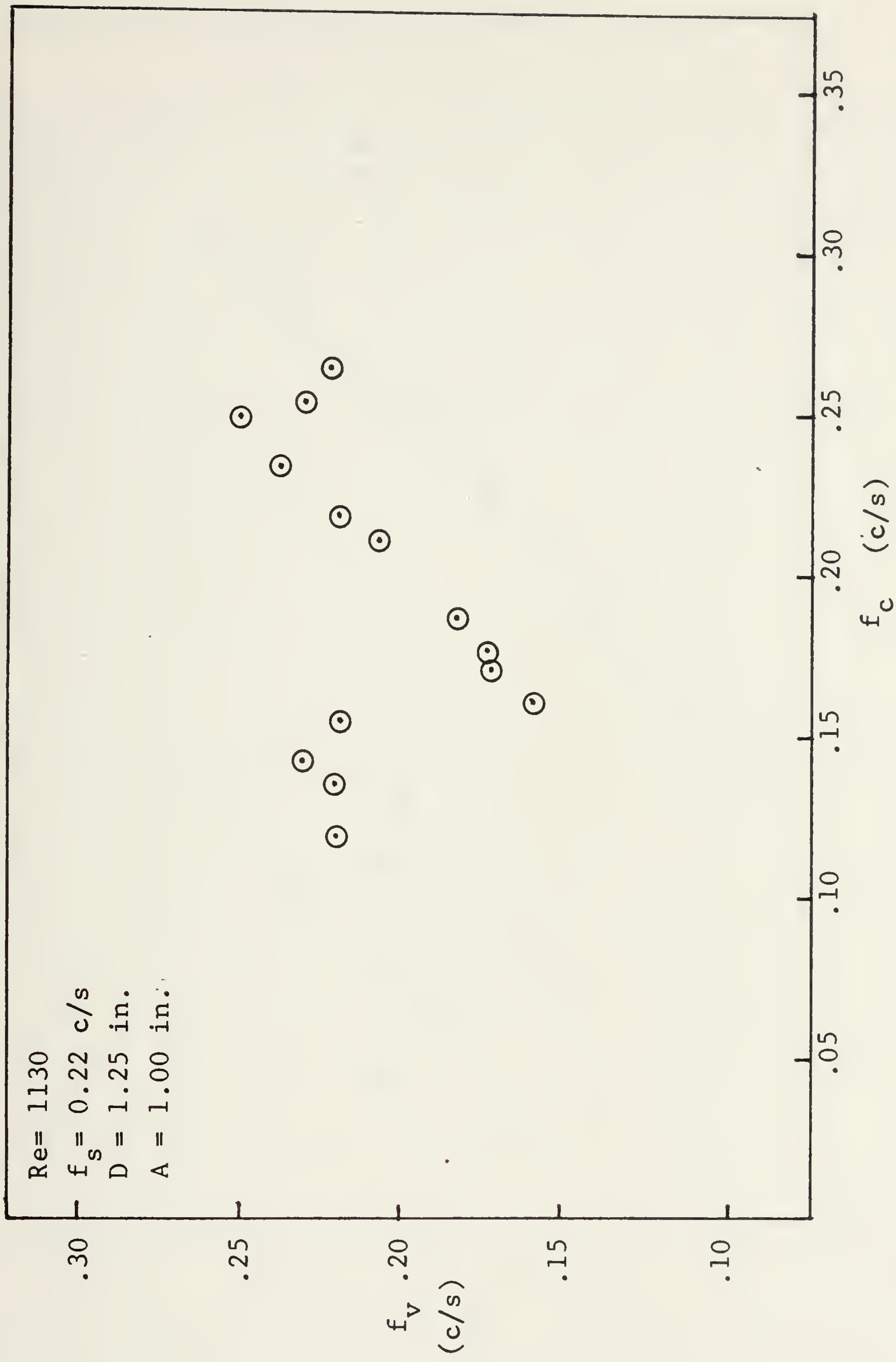
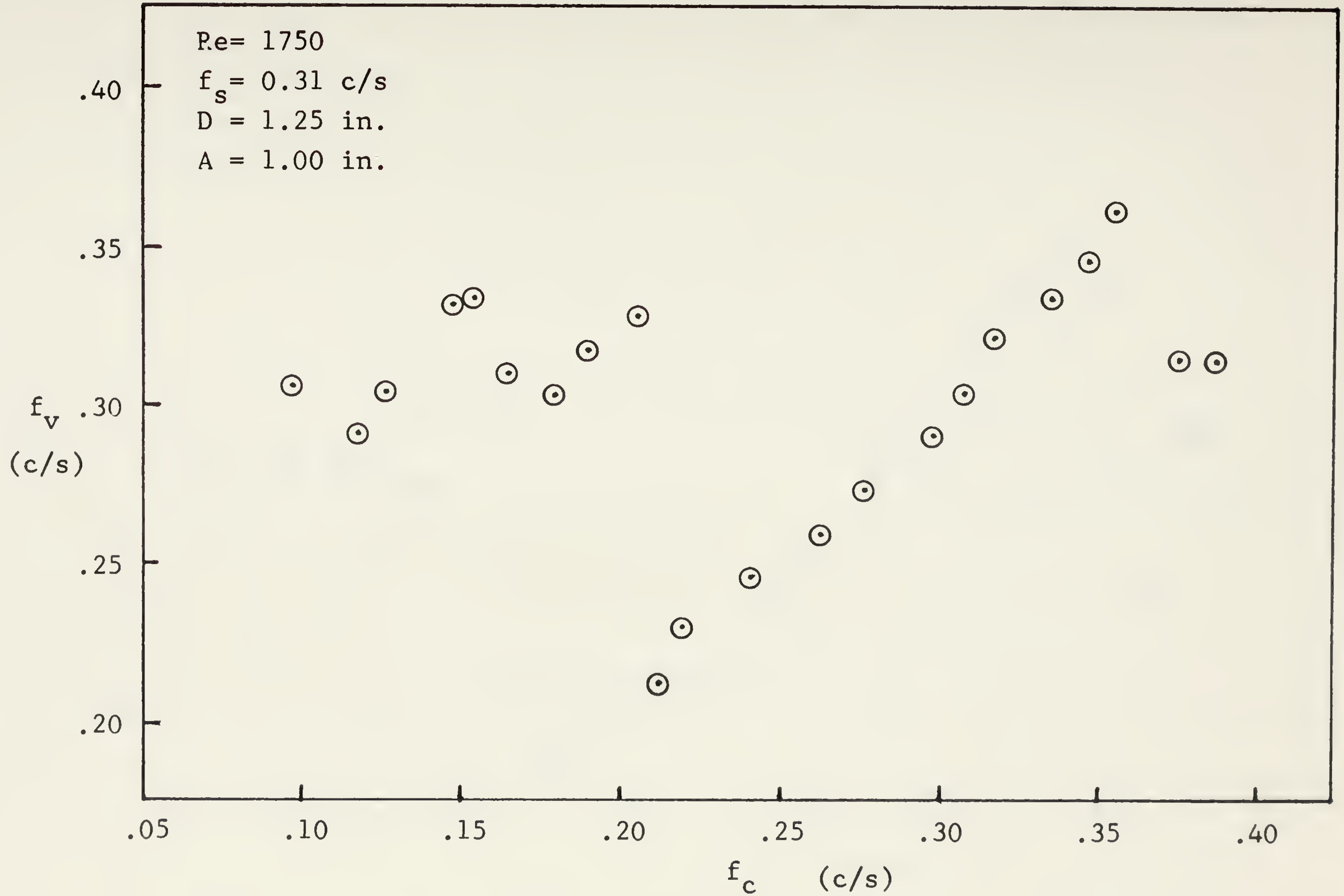
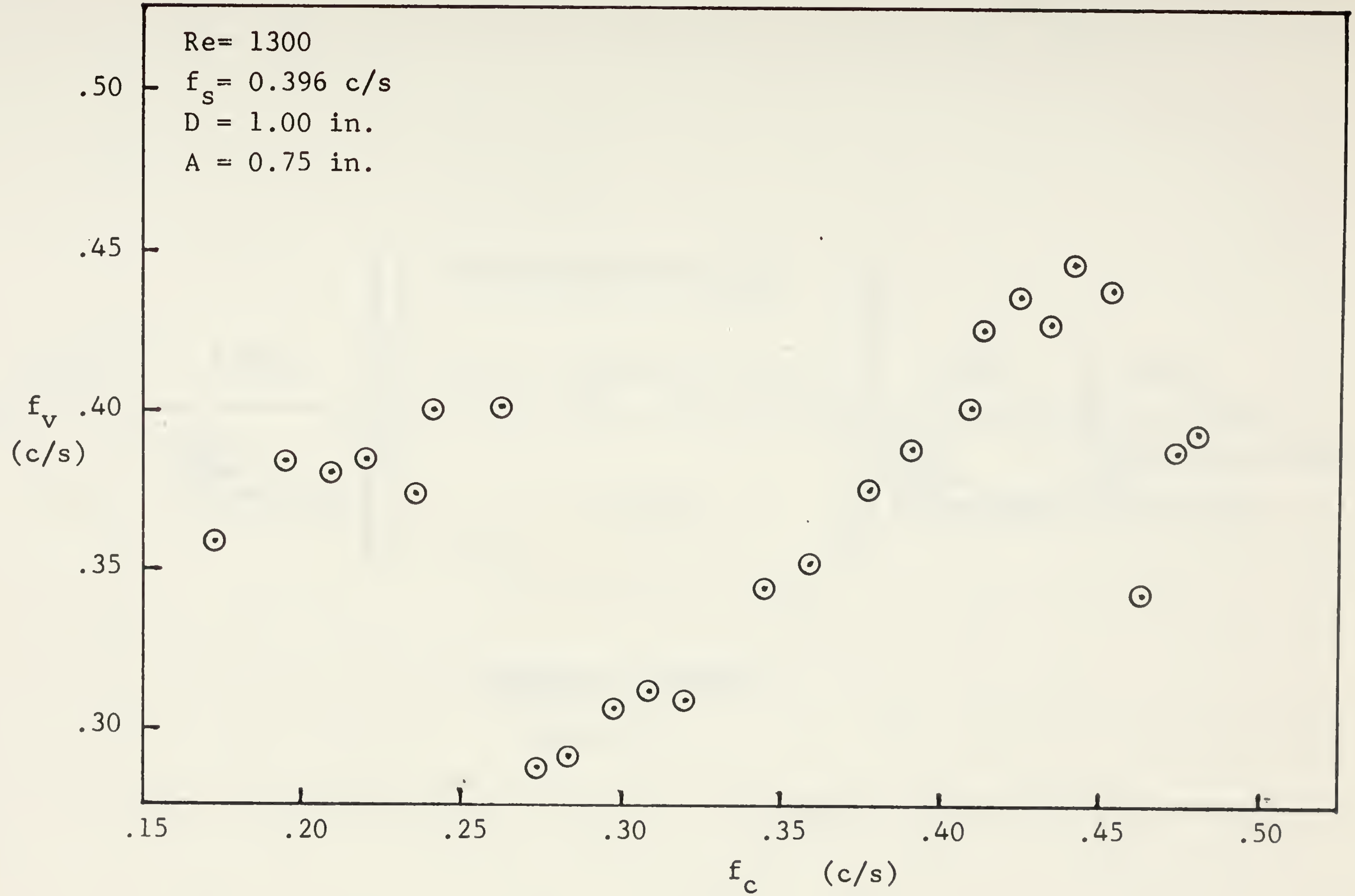

Re= 1130
f_s = 0.22 c/s
D = 1.25 in.
A = 1.00 in.
.05
.10
.15
.20
.25
.30
.35
f_c (c/s)
.30
.25
.20
.15
.10
f_v (c/s)

Figure 24



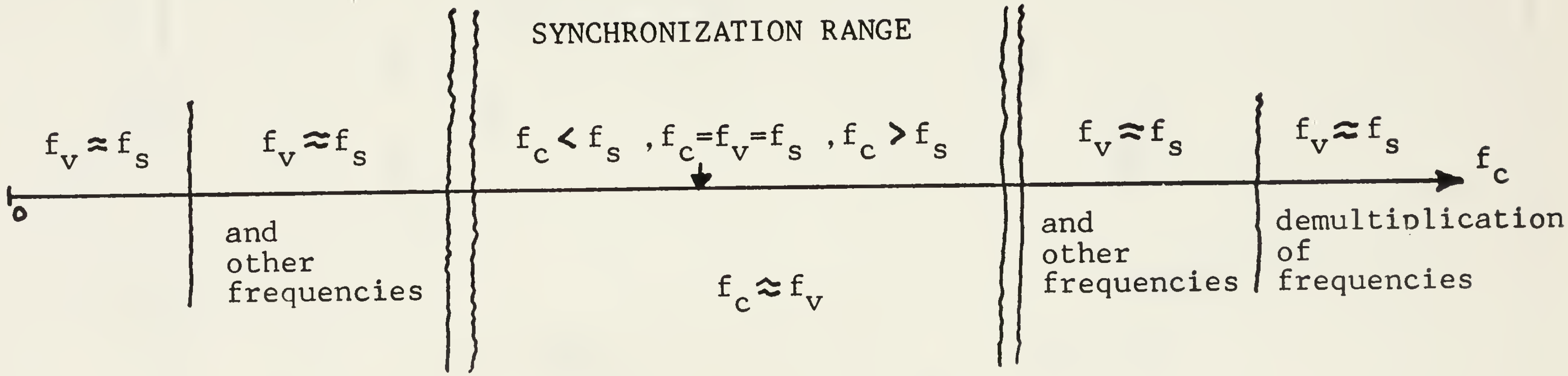
Re= 1750
f_s= 0.31 c/s
D = 1.25 in.
A = 1.00 in.
.40
.35
.30
.25
.20
f_v
(c/s)
.05
.10
.15
.20
.25
.30
.35
.40
f_c (c/s)

Figuer 25



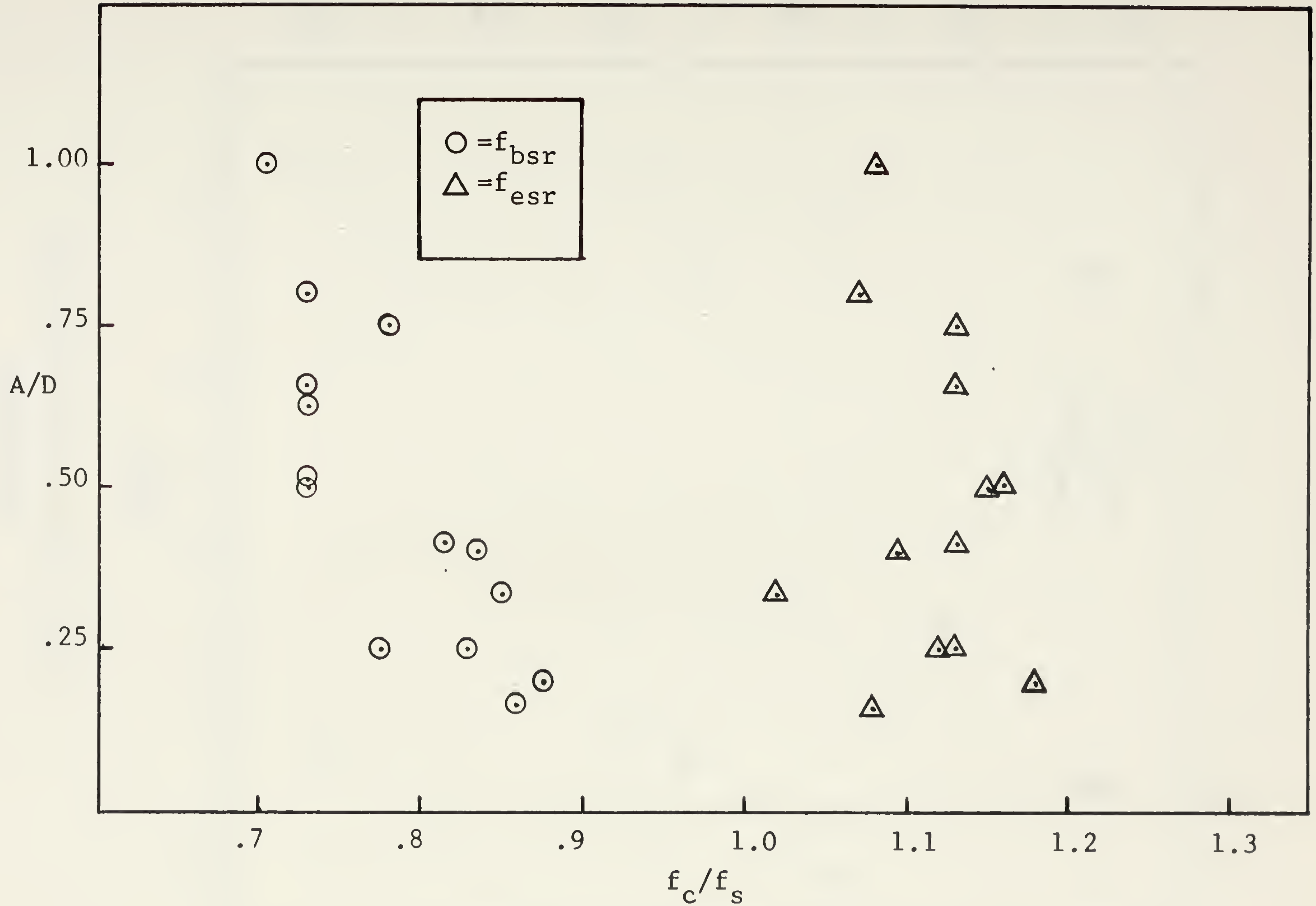
Re= 1300
f_s= 0.396 c/s
D = 1.00 in.
A = 0.75 in.
f_v
(c/s)
.50
.45
.40
.35
.30
.15
.20
.25
.30
.35
.40
.45
.50
f_c (c/s)

Figure 26

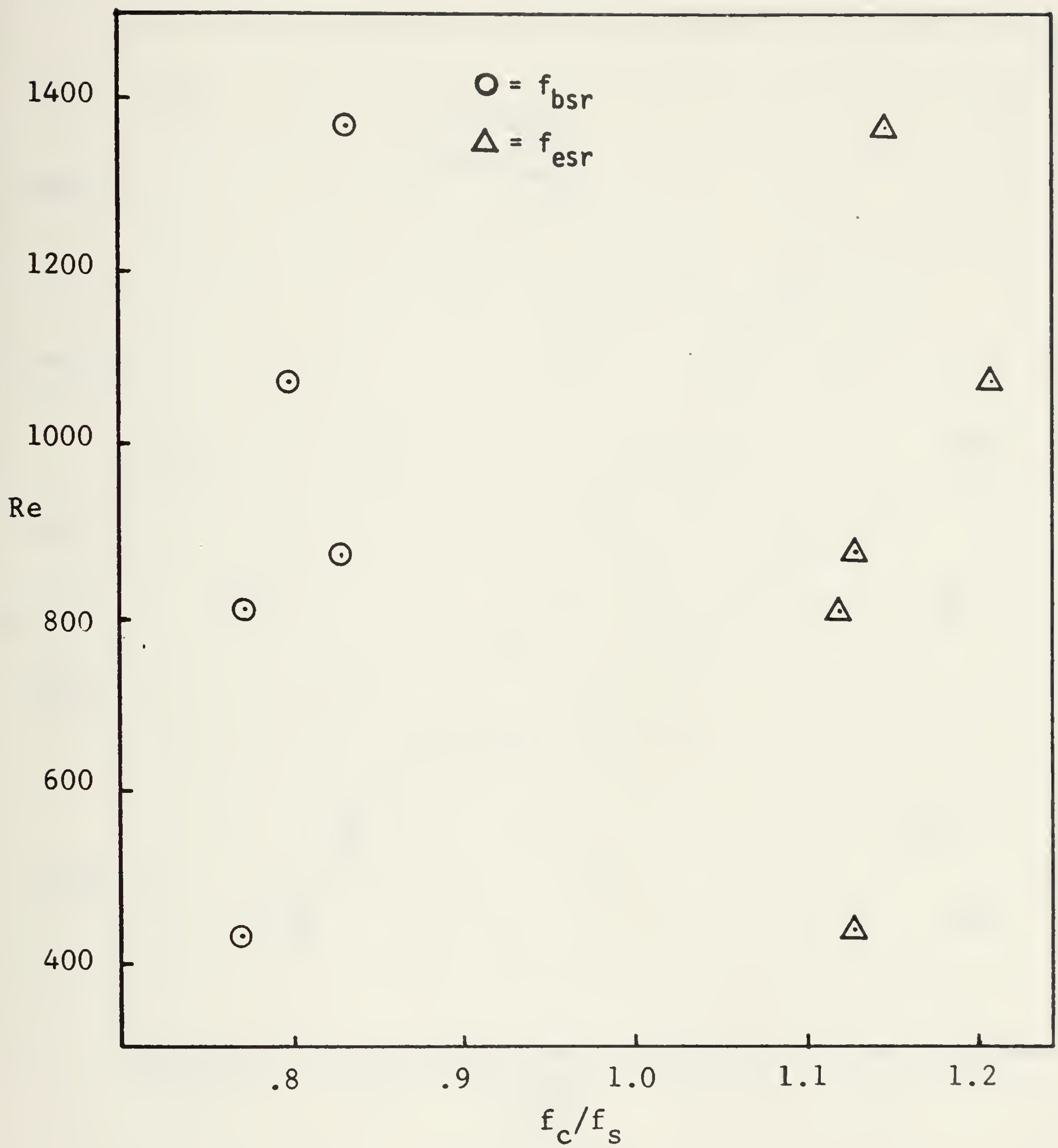


FREQUENCY SPECTRUM

Figure 27

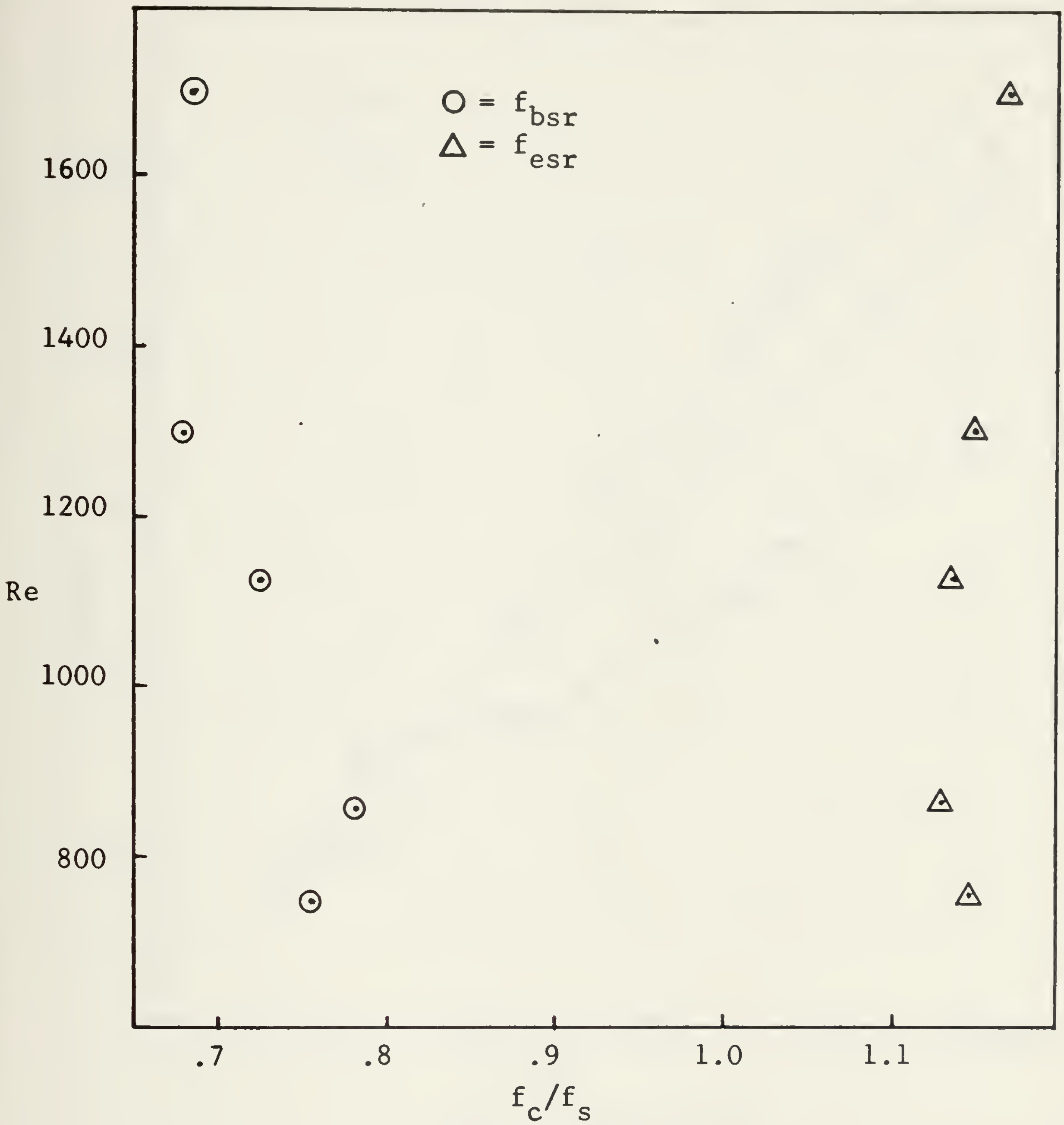


A/D versus f_c/f_s (Re= 860)
Figure 28



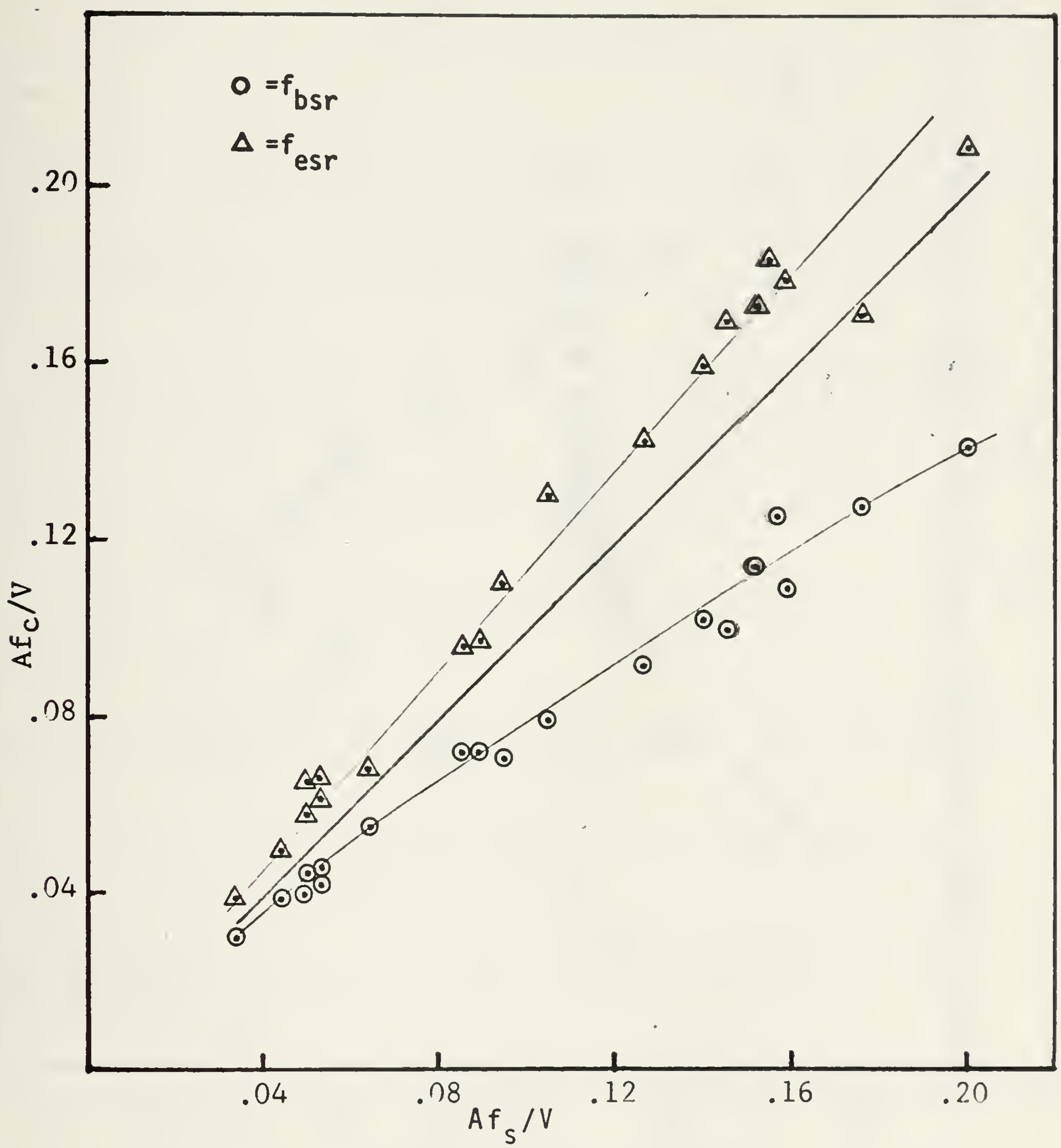
Re versus f_c/f_s (A/D = .25)

Figure 29



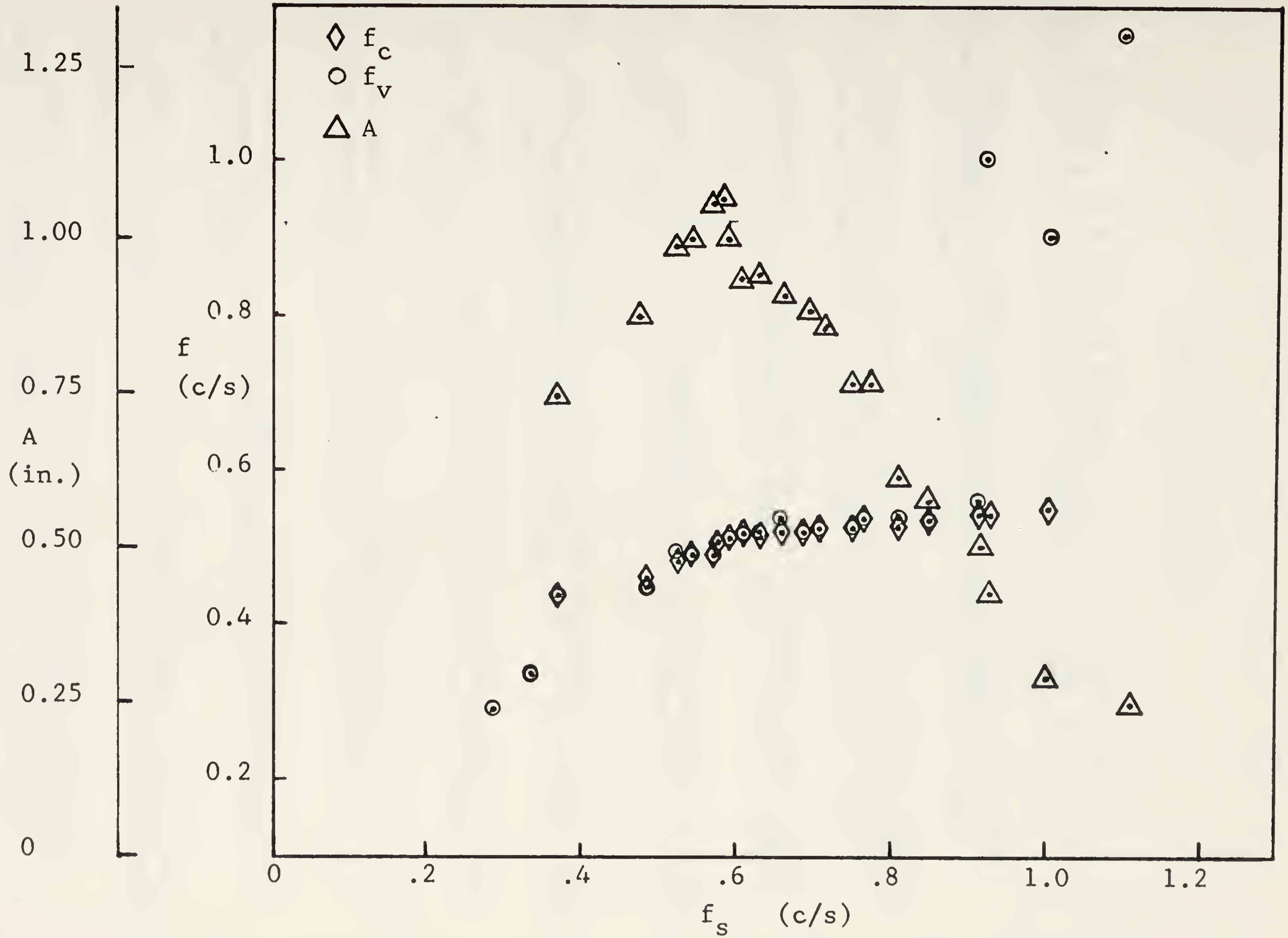
Re versus f_c/f_s (A/D = 0.75)

Figure 30



Af_c/V versus Af_s/V

Figure 31



Amplitude and Frequency of a Freely Oscillating Cylinder

Figure 32

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The interaction between the forced oscillations of a cylinder in flowing water and its vortex wake as well as the flow-induced oscillations of a string-suspended cylinder are examined. In the former case, the frequency of the vortex shedding and the range of frequency synchronization are determined for each cylinder, flow velocity, and the amplitude and frequency of the forced oscillations. In the latter case,

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the amplitude and frequency of the oscillation of the suspended cylinder as well as the frequency of the vortex shedding are determined. Finally, the results are reported in terms of appropriate normalized parameters and interpreted in the light of existing information.

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Flow about an oscillating cylinder and frequency synchronization.